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DEMONSTRATION/VALIDATION OF LONG-TERM MONITORING USING WELLS INSTALLED BY DIRECT PUSH TECHNOLOGIES

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The objective of this study was to demonstrate that long-term groundwater monitoring results from direct push wells agree with those from conventionally drilled wells, the currently accepted baseline technology. Five field sites were included in the study to represent a variety of geological conditions as well as a cross-section of regulatory domains (e.g. EPA regions and states). Direct push wells were installed adjacent to, and paired with existing conventional wells, drilled via hollow stem auger. The following sites were part of this effort: the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH (EPA Region 1); Dover National Test Site (DNTS) at Dover AFB, DE (EPA Region 3); the Naval Facilities Engineering Services Center (NFESC) at Port Hueneme, CA (EPA Region 9); Tyndall AFB, FL (EPA Region 4); and Hanscom AFB, MA (EPA Region 1). Five sampling runs were conducted over a fifteen month period at each site. Target groundwater chemical analytes included the following volatile organic contaminants (VOCs): tetrachloroethene (PCE), cis-1,2-dichloroethene (cis-DCE), trans-1,2-dichloroethene (trans-DCE), vinyl chloride (VC), benzene, toluene, ethylbenzene, o,m-xylene, p-xylene, 1,4-dicl=hlorobenzene (DCB)trichloroethane (TCA), and MTBE.

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EXECUTIVE SUMMARY

INTRODUCTION

During environmental site characterization, remediation, and compliance efforts, groundwater monitoring wells have served as the conventional tool-of-choice for accessing groundwater samples. Throughout characterization, remediation, closure, and afterward, critical decisions are based on data collected from monitoring wells that are installed. Generally such installation uses a drilling technique.

Recent increases in the application of direct push (DP) technologies during site characterization have led to more rapid and cost effective site characterization and other benefits. In addition, CPT and percussion-type DP rigs provide the ability to install groundwater monitoring wells that groundwater samples to be obtained more cost effectively than from conventionally drilled wells. Prior to this study, the most extensive use of DP wells has been only for initial site characterization. They are not yet widely accepted for long-term monitoring at remedial action sites. A need has existed for direct comparisons between conventionally drilled wells and DP wells to validate the usefulness of DP wells for long-term monitoring. If DP wells can be demonstrated to perform as well as drilled wells, widespread regulatory acceptance of these cost-effective methods should be forthcoming.

OBJECTIVES OF THE DEMONSTRATION

The objective of this study was to demonstrate that long-term groundwater monitoring results from DP wells agree with those from conventional drilled wells, the accepted baseline technology. A caveat of this approach is that comparing DP installed wells to conventional drilled wells with the intent to determine their validity implies that the conventional drilled wells produce empirically, or absolutely accurate monitoring results. In reality, there is no universally accepted standard monitoring well or sampling method that produces an absolutely accurate representation of the groundwater. This is important because the primary focus of this study is not to measure the accuracy with which samples from DP wells are representative of the groundwater, but rather to determine whether DP wells produce the same results, statistically, as conventional drilled wells. The benefit of validating direct push technology and promoting its acceptance and use for groundwater sampling would be to reduce the cost of well installations and long-term monitoring costs at remedial action sites.

SCOPE

Five field sites were included in the study to represent a variety of geologic conditions as well as a cross-section of regulatory domains (e.g. EPA regions and states). DP wells were installed adjacent to, and paired with, existing conventional wells, drilled via hollow stem auger (HSA), at the following facilities: the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH (EPA Region 1); Dover National Test Site (DNTS) at Dover AFB, DE (EPA Region 3); the Naval

Facilities Engineering Service Center (NFESC) at Port Hueneme, CA (EPA Region 9); Tyndall AFB, FL (EPA Region 4); and Hanscom AFB in MA (EPA Region 1).

Five sampling rounds were conducted over a 15-month period at each of the sites. Groundwater samples were collected and parameters typically monitored for long-term site compliance were evaluated (e.g. contaminant concentrations and other groundwater quality indicators). The target chemical analytes for this project included the following volatile organic contaminants: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-DCE), trans-1,2-dichloroethene (trans-DCE), vinyl chloride (VC), benzene, toluene, ethylbenzene, o,m-xylene, p-xylene, 1,4-dichlorobenzene (DCB), trichloroethane (TCA) and MTBE. Existing HSA wells were used at all sites except Port Hueneme, where NFESC installed new conventional and DP wells for this study. New DP wells were installed at all sites except Hanscom AFB, where such wells were installed in 1996 for a previous study.

REGULATORY ISSUES

The main regulatory concerns regarding the use of DP wells for long-term groundwater monitoring in place of HSA wells are as follows.

1. There is a need to demonstrate that there is no difference in groundwater chemistry between samples collected from HSA wells and those collected from DP wells for long-term (greater than one year) monitoring periods.
2. State regulators generally have minimum annular space sealing requirements based on drilled well specifications.
3. It is often speculated that annular sealing may not be complete for pre-packaged well screen devices and tremied filter pack applications under certain geologic conditions (e.g., clay formations).
4. An ASTM standard (D 5092) exists for filter pack design in drilled wells, but not for DP wells. Similar to annular sealing requirements, some state regulations explicitly require a filter pack designed to a formal specification.
5. Data do not exist to support the use of DP wells in a broad range of geologic conditions, thus reinforcing a tendency to accept them only on a case-by-case basis.

TECHNOLOGY DESCRIPTION

DP is used extensively as an alternative to drilling for the screening phase of a site characterization program and for temporary monitoring of remediation systems. DP approaches to site characterization provide detailed, continuous data on the subsurface stratigraphy in real time; produce little or no drilling waste; limit worker exposure to hazardous materials; and increase speed compared to conventional drilling and sampling.

DP is also ideally suited for installing small diameter monitoring wells (0.5 to 2.0 inch). In one method, an exposed-screen monitoring well is pushed into place on the outside of CPT rods. In another method, pre-constructed wells, sometimes including prepacked screens are emplaced through the inside of the drive rods after the rods have been advanced to depth.

Installing monitoring wells via conventional (HSA) drilling is typically a time consuming and costly component of site characterization and monitoring. DP wells are less costly

for a number of reasons. In most formations, DP is minimally intrusive and causes less disturbance of the natural formation than many conventional drilling techniques. Worker exposure and disposal costs associated with investigative derived waste (IDW) are reduced with DP because, in contrast to drilling, it generates little or no potentially contaminated drill cuttings. Since many DP wells have a smaller diameter than traditional wells, purge water volumes, sampling time, and indirect waste disposal costs are reduced for most sampling activities.

However, the installation of DP wells is limited to unconsolidated soils and sediments including clays, silts, sands, and some gravels and cobbles, depending on the weight of the push equipment. Direct push methods cannot be used to install monitoring devices in consolidated bedrock, deposits containing significant cobbles and boulders, or in heavily cemented materials.

From an operational standpoint, regulatory constrained sampling protocols sometimes limit the performance of smaller diameter (e.g., <1 inch) DP wells. The widely mandated low-stress (low-flow) sampling protocol for volatile organic compounds specifies drawdown limits within the well. If the limits are exceeded, it is assumed that the aquifer has been unacceptably stressed. Well production for a given drawdown is proportional to the square of the well diameter. Therefore, in conforming to the requirements of the low-flow protocol, smaller diameter DP wells must sometimes incur long purge times.

STUDY DESIGN

Groundwater sampling was performed according to the EPA's low-stress sampling procedure. Standard EPA methods specified in *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846, 3rd Edition* (USEPA, 1996) were identified as the most appropriate analytical methods for evaluating VOCs in groundwater for this study. Primary analytical procedures for VOAs conformed to SW-846 standard 8021B. This analytical method for monitoring volatile organic compounds (VOCs) was selected based on feedback from the regulatory community and in consideration of the relevance of the anticipated results to long-term regulatory monitoring. Methods for evaluating inorganic species were selected to match the parameter list developed by NFESC on a previous project thereby yielding a larger dataset for analysis.

Statistical tests of hypothesis were used to compare the performance of DP wells to that of HSA wells for groundwater monitoring. Hypothesis testing was conducted on the differences between the samples collected from the DP wells and the samples collected from the conventionally installed wells. Paired-sample statistics were used for the testing. Both parametric and non-parametric tests exist for the purpose of hypothesis testing, and the applicability of each type depends on the distribution of the population, as inferred from the distribution of the random sample obtained.

The test most appropriate to each sample distribution observed was conducted on the paired data. In all hypothesis testing, pairs of analytical non-detects were not included in the set, reducing the degrees of freedom N by one for each tie discarded.

The statistical methodology used to evaluate the data is illustrated in the flow chart in Figure 1

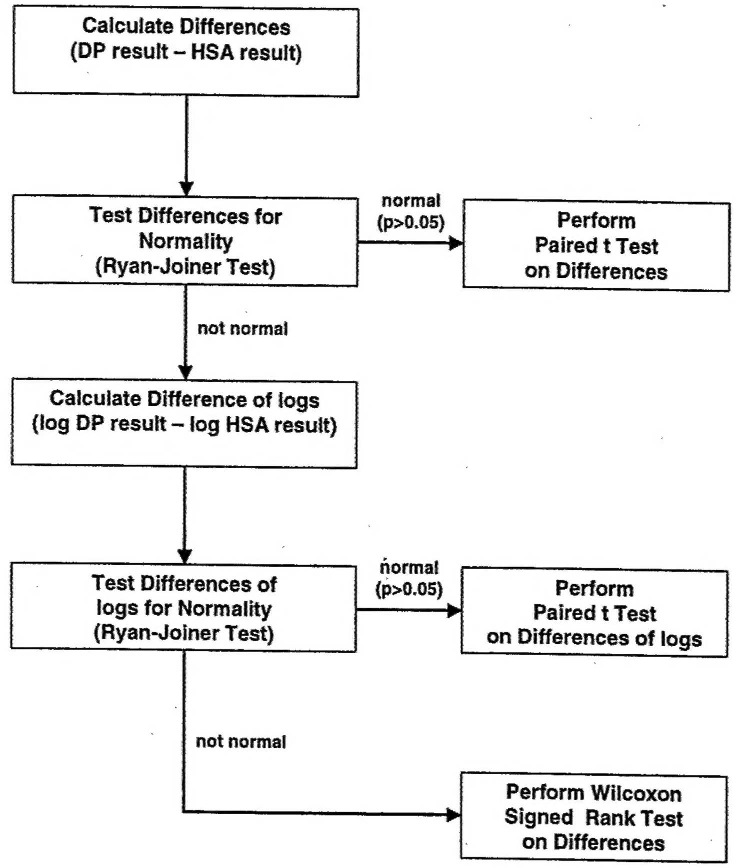

Figure 1. **Flow chart of process for statistical tests of hypothesis**

There are two ways of making an incorrect decision in hypothesis testing. In a *type I* error, the sample data reject the null hypothesis even though it is true. In a *type II* error, the data support acceptance of the null hypothesis even though it is false. In this study, a type I error would result in improper rejection of DP wells, whereas a type II error would result in improper acceptance of DP wells

The level of significance, α, is the probability of a type I error. The *confidence* of the test is 1-α. In most applications of environmental regulatory concern, a confidence of 95% (α =0.05) is considered acceptable, and was the standard of performance for this study.

The *P-value* is the smallest significance (α) at which the null hypothesis can be rejected for the given random sample. At 95%, any P-value in excess of 0.05 results in acceptance of the null hypothesis.

The probability of a type II error is denoted by β. *Power* (1- β), can be thought of as the test's ability to detect a difference between DP and conventional well types from the sample should one really exist in the general population. It is the proportion of experiments, if indefinitely repeated, that would falsely conclude sameness in future experiments. For this study, a power of 80% was regarded as desirable, but was not enforced *a priori* via study design, because the population variance for each set of measured differences was neither known nor estimable in advance; it can only be estimated from the sample variance once data are collected.

RESULTS

The results of the statistical testing indicate that, by and large, there was no statistically significant difference between groundwater monitoring results from DP wells and those from HSA wells. In every case in which the null hypothesis was rejected, the mean difference was greater than zero. Because the differences were calculated as the DP well result minus the HSA well result, this indicated that, in these cases, the DP wells produced more conservative contaminant monitoring results (i.e., higher concentrations) than the HSA wells.

In general, the 2" non-packed DP wells and 0.75" non-ASTM prepacked DP wells agreed most often with the HSA wells, whereas the 1.5" non-packed wells disagreed most often, but were the most conservative. The pre-packed 0.5" wells were least conservative overall. For MTBE, all DP well types were found to agree with HSA wells, but this was the only parameter available for evaluation of the ASTM pre-packed wells and the 0.75" non-packed wells.

Analyses for inorganic species and other water quality parameters were conducted on samples from four rounds of sampling at all sites. The results of the inorganics analyses were analyzed by the same statistical procedures as the VOA results. Interesting to note is that for the non-packed DP wells and the non-ASTM prepacked DP wells, the results from the DP wells are consistently higher than those from the HSA wells, but for the ASTM prepacked DP wells, the sign of the difference is mixed among analytes. Overall, the 2" DP wells with ASTM prepacked screens disagreed most often with the HSA wells, while the unpacked 0.75" wells agreed in every case.

The *power* of all hypothesis tests was evaluated. Only a handful of the comparisons met or exceeded the goal of 80% *power* and, in general, the *power* of the tests involving inorganics was greater than for those involving VOCs. This finding is likely due to the linear distribution of inorganics data relative to VOCs (which can span several orders of magnitude), a fact is also reflected in the greater number of inorganics data sets that exhibited normal distributions without transformation. Additional sampling of the existing wells in the study is recommended as the most cost effective way to raise the *power* of all the tests of hypothesis.

COST ASSESSMENT

Typical cost savings associated with direct push wells versus traditional wells are generally realized during the installation and well development phase. Although smaller diameter wells may purge faster, with few exceptions operational costs are no different when compared to conventional monitoring wells.

TECHNOLOGY IMPLEMENTATION

One of the ways in which the technology will be transferred to the user is through the marketing and sales efforts of the DP industry. Industry was involved extensively during the demonstration. Applied Research Associates, Inc. (ARA), a leading provider of CPT equipment and services, including DP well installation, was critical member of the project team. Geoprobe Systems, Inc. (Geoprobe), the foremost manufacturer of percussion hammer DP platforms and related equipment, also participated, conducting

well installations at two of the test sites. In addition, ARA, Geoprobe, and many other industry players contributed to preparation of an ASTM standard that ARA authored under in-kind contribution to this project. The ASTM subcommittee on direct push technology (D18-21) includes representatives of 18 DP practitioners and 3 producers of DP equipment, and the subcommittee chair serves on the DOD Task Force on Direct Push Ground Water Monitoring Wells, which was actively engaged in the study.

DEFICIENCIES

Although several project objectives were met unequivocally, the desired *power* of the statistical tests was not achieved. One reason why the tests lacked sufficient statistical *power* may be that the study objectives changed subsequent to establishing the experimental design. Originally, the study was conceived as a gross comparison of DP versus HSA wells, admitting primarily the installation technique as the variable of interest. This plan called for aggregating the monitoring results from similarly constructed DP wells for the purposes of hypothesis. For instance, 2" and 1.5" diameter with no pack would be combined and all 0.75" wells regardless of pack type would be combined. However the objective transformed during the project to one of evaluating each combination of DP pack type and diameter individually. *Power* increases or decreases in relation to the number of independent observations in a *sample*. Splitting failing to aggregate observations as originally planned diminished *power*.

RECOMMENDED NEXT STEPS

Given the present objective of evaluating each combination of DP pack type and diameter individually against HSA wells, it is recommended that significantly more sampling rounds be undertaken to improve the *power* it the hypothesis tests. *Power* increases with the number of independent observations in the statistical sample (e.g., the number of sampling rounds conducted on the well pairs used for the study). With that in mind, recommendations toward increasing statistical *power* require increasing the number of observations.

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1. Introduction

1.1 Background Information

During environmental site characterization, remediation, and compliance efforts, groundwater monitoring wells have served as the conventional tool-of-choice for accessing groundwater samples. A typical sequence of events in the life cycle of a contaminated site would include the discovery of a release, an initial source removal response, initial site characterization efforts, generation of a conceptual model, detailed site characterization efforts, remedial design, remedial system installation efforts, system performance monitoring, compliance monitoring and site closure. Monitoring wells are generally installed at key steps in this sequence of events. To define the extent of the contaminant plume, determine where and how fast it is migrating, select an optimal remediation method, evaluate the effectiveness of a remedial option, and to serve as monitoring tools for compliance purposes. In most cases, critical decisions are based on data collected from wells that are installed using a drilling technique.

In hazardous waste site assessments it is necessary to detect, delineate, and identify contaminants and to further characterize subsurface conditions. Current practice often requires multiphase efforts with many site visits, using geophysical methods as well as soil borings and monitoring well installations, all of which significantly impact the overall cost of characterizing and monitoring the site.

Recent increases in the application of direct push technologies during site characterization have led to more rapid site characterization and development of more detailed conceptual models of hydrogeologic structure. The Cone Penetrometer Test (CPT) (ASTM D 6067) is an excellent tool for mapping stratigraphy and finding target layers for sampling. Other sensors such as electrical conductivity and optical contaminant detectors have been placed on direct push systems. Direct push soil (ASTM D 6282) and water sampling (ASTM D 6001) can be used in lieu of drilling to rapidly determine contaminant distributions and identify strata of concern.

Recently developed direct push technologies (e.g., CPT and percussion rigs) provide the potential to collect groundwater samples more efficiently and at lower cost than from conventionally drilled wells. So far, the most extensive use of these technologies has been only as initial site characterization tools. They are not widely accepted for installing long-term monitoring wells at remedial action sites. Direct comparisons between conventionally drilled wells and direct pushed (DP) wells need to be conducted to validate the usefulness of DP wells for long-term monitoring. If DP wells can be demonstrated to perform as well as drilled wells, widespread regulatory acceptance of these cost-effective methods should be forthcoming.

1.2 Objectives of the Demonstration

The purpose of this project was to rigorously compare the results of laboratory analyses conducted on samples obtained from direct push (DP) wells to those obtained from wells

installed utilizing conventional techniques (e.g., hollow-stem auger (HSA) wells). The benefit of validating direct push technology and promoting its acceptance and use for groundwater sampling would be to reduce the cost of well installations and long-term monitoring costs at remedial action sites.

Although DP-installed monitoring points have been accepted by the regulatory community for characterization of a groundwater contamination plume, there was, until now, little data to support their use for long-term regulatory monitoring (EPA 1996). This project implemented a rigorous sampling effort to establish a database of water quality and chemical analytical results comparing samples from both well types over a 15-month period. These data were analyzed using statistical tests of hypotheses to determine whether any significant difference existed in the measured groundwater quality parameters obtained from the two well types.

Regulatory approved protocols for well installation and development, groundwater sampling, and field and laboratory analytical methods were specified and adhered to, ensuring the results of the experiment were valid in a regulatory context.

Five field sites were included in the study to represent a variety of geologic conditions as well as a cross-section of regulatory domains (e.g. EPA regions and states). DP wells were installed adjacent to, and paired with, existing auger-drilled wells at the following facilities: the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH (EPA Region 1); Dover National Test Site (DNTS) at Dover AFB, DE (EPA Region 3); the Naval Facilities Engineering Service Center (NFESC) at Port Hueneme, CA (EPA Region 9); Tyndall AFB, FL (EPA Region 4); and Hanscom AFB in MA (EPA Region 1).

Five sampling rounds were conducted over a 15-month period at each of the sites. Groundwater samples were collected and the parameters examined under long-term site compliance monitoring were evaluated (e.g. chemical concentrations, oxidation-reduction potential (ORP), pH, temperature, conductivity, turbidity, and dissolved oxygen (DO)). The target analytes for this project included: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-DCE), trans-1,2-dichloroethene (trans-DCE), vinyl chloride (VC), benzene, toluene, ethylbenzene, o,m-xylene, p-xylene, 1,4-dichlorobenzene (DCB), trichloroethane (TCA) and MTBE. Existing conventional wells were used at all sites except Port Hueneme, where NFESC installed new conventional and DP wells for this study. New DP wells were installed at all sites except Hanscom AFB, where such wells were installed in 1996 for a previous study. Plans detailing the specific well construction details at each site are provided in Appendix B.

1.3 Regulatory Issues

The main regulatory concerns regarding the use of DP wells for long-term groundwater monitoring in place of conventionally drilled wells are as follows.

1. There is a need to demonstrate that there is no difference in groundwater chemistry between samples collected from HSA wells and those collected from DP wells for long-term (greater than one year) monitoring periods. These analytical results must be supported by appropriate statistical tests, applied to groundwater sample data collected from comparably constructed DP and conventionally drilled wells.

2. State regulators generally have minimum annular space sealing requirements based on drilled well specifications. These specifications often preclude the use of small diameter DP wells for long-term monitoring, since annular spacing is limited by the diameter of the push tool. In the case of direct-contact wells (i.e., those whose outer surface is in intimate contact with the soil formation due to displacement during driving) there is no annular space.
3. It is often speculated that annular sealing may not be complete for pre-packaged well screen devices and tremied filter pack applications under certain geologic conditions (e.g., clay formations).
4. An ASTM standard (D 5092) exists for filter pack design in drilled wells, but not for DP wells. Similar to annular sealing requirements, some state regulations explicitly require a filter pack designed to a formal specification. There is therefore an institutional barrier to the use of direct-contact DP wells or DP wells, which do not employ a conventional filter pack.
5. Data do not exist to support the use of DP wells in a broad range of geologic conditions, thus reinforcing a tendency to accept them only on a case-by-case basis. This demonstration attempts to provide the necessary data to alleviate regulatory concerns about DP well applicability in a broad range of geologic conditions.

1.4 Previous Testing of the Technology

Several studies have evaluated the use of direct push technology for well installation, comparing the DP wells to conventional (auger-drilled) wells (McCall, *et. al.*, 1997, McCall, 1999). None of the studies, however, focused on long-term data quality in the comparisons.

Beginning late in 1995, Applied Research Associates, Inc., under contract with the Air Force Research Laboratory began a program to compare the performance of direct push and conventional monitoring wells for long-term groundwater monitoring of corrective action sites. Sites at Hanscom Air Force Base (AFB) and Hanscom Field in Massachusetts were selected for this initial study. A comprehensive Work Plan was prepared that included protocols for well installation, sampling, chemical analysis, and statistical comparisons, as well as a site specific Health and Safety Plan (HASP) and Quality Assurance Project Plan (QAPP). DP wells were successfully installed adjacent to 43 existing conventional monitoring wells, creating matched well pairs installed to depths ranging from 13 feet to 65 feet. Screen lengths, elevations of screened intervals, and well diameters were matched as closely as possible in all pairs.

Two rounds of sampling and analysis were completed, adhering strictly to a low-stress (low-flow) sampling protocol and evaluating a suite of ten volatile organic analytes determined by EPA SW-846 methods. Paired data statistical tests were used to compare the performance of the two well types because of their ability to neutralize the influence of extraneous factors (e.g., location of the well pair within the contaminant plume, location with regard to local variation in the hydrogeology, length and depth of the screened interval, etc.) which may vary from pair to pair but are assumed to have the same influence within each pair.

Statistical testing was conducted on nine analytes and five water quality parameters that were measured during purging of the wells for sample collection. The parametric Student's *t*-Test and non-parametric and Wilcoxon Signed Rank Test were applied to the data set, as appropriate, to test the null hypothesis that the mean of differences between paired observations was equal to zero.

With only one exception among all analytes and water quality parameters for which results were compared, the results showed no statistically significant difference between the performance of the two well types. However, due to ongoing remediation efforts at the sites, the data generated during the study produced a large number of non-detects, which complicated the statistical analyses and decreased the number of observations in the statistical samples, thus limiting the power of the tests.

The US EPA Technology Innovation Office (TIO) (Crumbly, 2000) conducted an independent review of the data. They concluded that the limited data set warranted additional sampling in more diverse geological settings. Thus, the current study expanded both the number of sampling events as well as the number and geologic diversity of sites involved.

2. Technology Description

2.1 Description

DP has been used to obtain site stratigraphic information and soil structural properties for several decades. DP is sometimes used as an alternative to drilling for the screening phase of a site characterization program and for temporary monitoring of remediation systems. DP approaches to site characterization and monitoring offer the significant advantages of providing detailed, continuous data on the subsurface stratigraphy in real time; producing little or no drilling waste; limiting worker exposure to hazardous materials; and increased speed compared to conventional drilling and sampling. Due to the high cost of drilling at their contaminant sites, both the Department of Defense (DOD) and the Department of Energy (DOE) have aggressive programs to develop chemical sensors and sampling methods for minimally intrusive direct push methods such as the Cone Penetration Testing (CPT) (Gildea, et al., 1995; Montgomery, et al., 1996; Farrington and Bratton, 1997).

Various methods have been used for the installation and construction of small diameter DP monitoring wells (0.5 to 2.0 inch). In one of the methods a DP monitoring wells may be installed in mandrel fashion with a bare screen and casing pushed into place over CPT rods. In the mandrel installation procedure the steel expendable point becomes the bottom cap to the well casing. Alternatively, DP monitoring wells may be constructed using prepacked screens that are installed through the ID of the drive rods after the rods have been advanced to depth. In this construction method a plastic cap or adapter separates the expendable point from the well bore.

Since this demonstration compares conventionally installed monitoring wells to DP-installed monitoring wells, a description of the HSA and DP types of wells is warranted.

Additional detail on installation of conventional and DP wells is provided under the heading of Physical Description and Operation (Section 4.2).

Conventional monitoring wells are installed by first drilling a borehole, removing the soil from the ground as depicted in Figure 1.

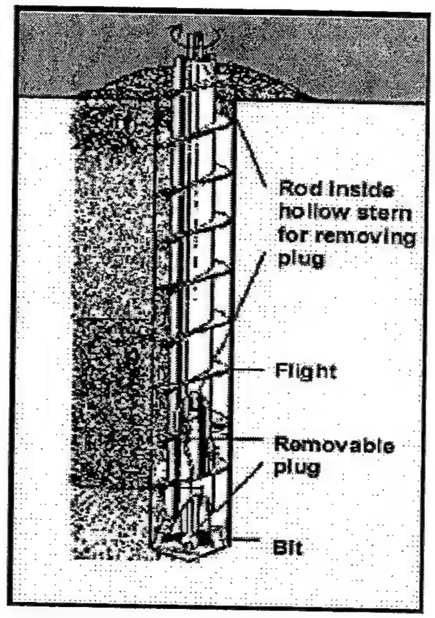

Figure 1. Typical Hollow-stem augers used to install conventional monitoring wells.

In the case of conventionally drilled wells, the borehole is held open by the hollow stem augers that are used to bore the hole. The well casing is typically constructed of schedule 40 polyvinyl chloride (PVC) but may also be constructed of steel or stainless steel. Well casings are typically 2 or 4 inches in diameter but may vary from one-half inch to 8 inches or larger. The well casing is lowered down inside the hollow stem auger to the design depth and a sand backfill is placed around the screened section as the augers are carefully removed. Above the screen section a seal is typically installed to prevent migration from geologic units above the screen down along the well casing. This seal is typically two to four feet in thickness and constructed of bentonite clay. The remainder of the hole is back filled with a cement grout and a concrete cap is installed at the surface.

There are two basic types of DP well systems exposed screen and protected screen. The direct push water-sampling guide, ASTM D-6001, describes both the concepts in detail. Exposed screens are driven with the well screen in contact with the surrounding formation. In protected screen configurations, the screens are enclosed in the push rods or casing, which is retracted after reaching the target installation depth. Protected screen configurations can incorporate either (expanding) pre-packed filter systems, tremied filter systems, or no filter system to fill the annular space between the screen and the formation left by retraction of the protective casing.

For the exposed screen method, a CPT or other direct push rig and rod string is utilized to install a direct-contact well, also classified as an exposed screen sampler (ASTM D 6001), as shown in Figure 2. The well material is pulled into the ground by the CPT rods, which are in compression, using the weight of the CPT truck as reaction mass. The details of the installation procedure are discussed in Section 4.2.2 (DP Well Installations - Exposed Screen Wells). With these wells the choices for casing size are limited as compared to conventional wells, since the well material has to fit closely around the outside of the rods. Casing sizes are typically 1½-inch or 2-inch nominal diameter. This system was chosen as the primary DP well type for this study because it allows the closest match of well construction details (slot size, screen length, diameter, and material) between DP and conventionally drilled wells. The well screen section on both DP and conventional wells can be varied in length depending on the requirements of the well, but the DP well screens were designed and installed to match the conventional well screen lengths and depths as closely as possible. Openings in the screen, typically called slots, allow the water to pass into or out of the well. The slots are designated by the width of the slot, typically 0.010 inch or 0.020 inch (10-Slot or 20-Slot, respectively). For this study, slot widths for the DP wells were designed to match the conventional well slot widths.

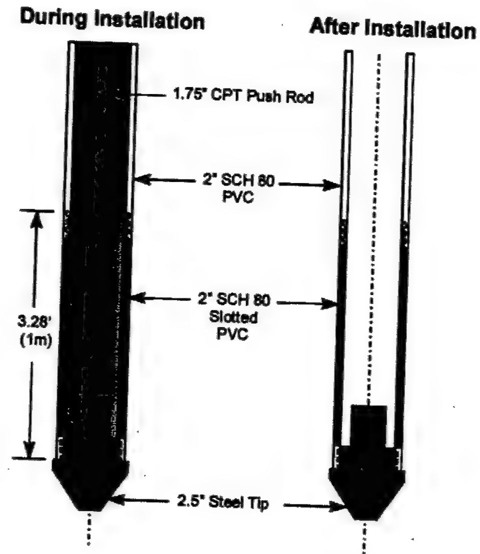

Figure 2. Installation of an Exposed Screen DP Well Type

Exposed screen wells do not have sand pack back fill because they do not provide an annular space between the well material and surrounding formation. Also, since the outer well screen is exposed during driving, rigorous development is necessary following installation to remove sediments from the screen slots and ensure the screened interval is free of any potential contamination acquired while passing though a higher stratum. ASTM D 5521 provides guidance on well development. The use of a surge block in combination with continuous groundwater withdrawal was used to develop the wells associated with this project.

Some DP well installations for this project also include protected screen systems incorporating pre-packaged filter packs. Specification of filter pack and casing screen slot criteria were based on grading curve results and recommendations presented in ASTM D 5092.

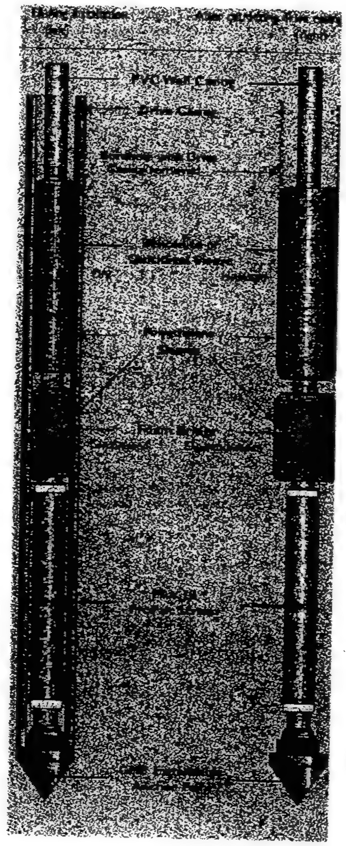

Figure 3. Installation of a Pre-Packed, Protected Screen DP Well Type

The technique for installing pre-packed protected screen systems is illustrated in Figure 3. A DP device is used to install and seal, in-place, these small diameter wells in one pass. These smaller wells are often installed using a Geoprobe® or similar machine that uses a percussion hammer to drive the well into the ground. The well installation system consists of an expendable drive point connected to a schedule 40 PVC riser pipe. An expandable annular seal is threaded immediately above the screened section. As the drive casing is removed, the seal expands to 2.5-inch (6.4-cm) outer diameter, effectively preventing grout intrusion into the screen interval. A seal is placed in the annulus between the borehole and the riser pipe on top of the expandable seal by use of a bentonite sleeve. Sufficient time is allowed for bentonite hydration and expansion prior to grouting the remaining annulus. The volume and elevation of the bentonite seal material is measured and recorded on the well completion diagram. Alternatively, non pre-packed wells can be installed with the protected screen approach, and the annular space filled by tremie insertion of filter pack and seal material.

Geoprobe® prepacked screen wells were installed at the Tyndall AFB and CRREL study sites for use during this study. The following description outline the technique used to install these wells. Initially, the drive rods are advanced to the desired depth with an expendable (anchor) point inserted in the lead rod Figure 4. Following this the prepacked screen(s) and PVC riser are assembled and lowered through the sealed bore of the drive rods. The drive rods are slowly retracted as the screen(s) is (are) held in position Figure 5). After formation collapse or gravity installation of sand to form the grout barrier, tremie installation of the annular seal and grout may be conducted using widely accepted grout mixtures (Figure 6). This construction method provides a filter pack and the well seal and annular seal recommended in ASTM D 5092 and required by most state regulatory agencies.

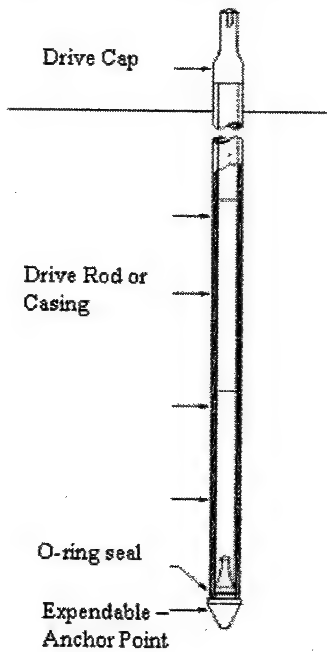

Figure 4. Advancing sealed drive rods or casing to depth for installation of prepacked screen monitoring well.

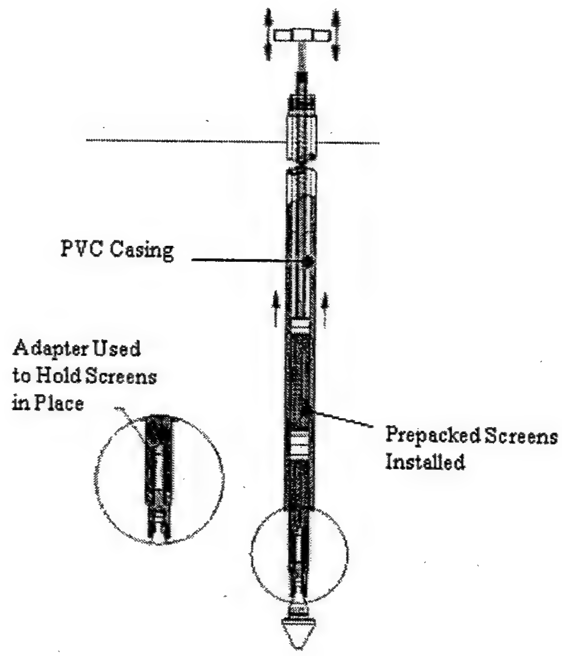

Figure 5. The drive rods are retracted and the prepacked screens remain in place providing accurate placement of filter pack.

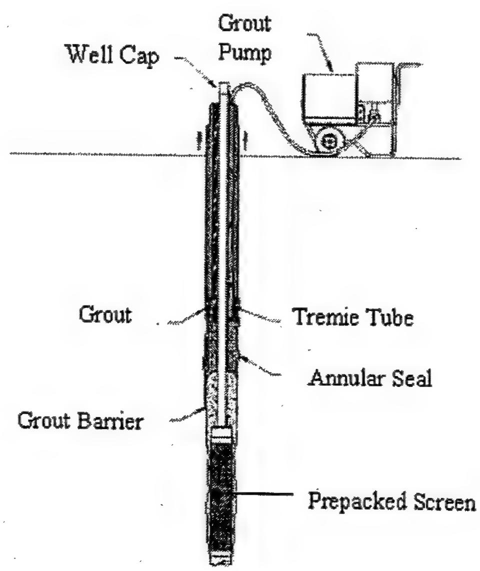

Figure 6. : Following placement of the grout barrier and well seal annular grout may be pumped in with a tremie tube from the bottom up if required.

For all well installations in this study, protective casings or access covers were installed to secure and protect the wells. At-grade access covers were set in concrete pads, which were sloped to promote water drainage away from the well. The top of the riser pipe was notched so that measured water levels maintained a constant location (vertical and horizontal) reference. Labels were affixed to the vault lids to mark the well location ID. Figure 7 illustrates a typical well completion, including the surface seal.

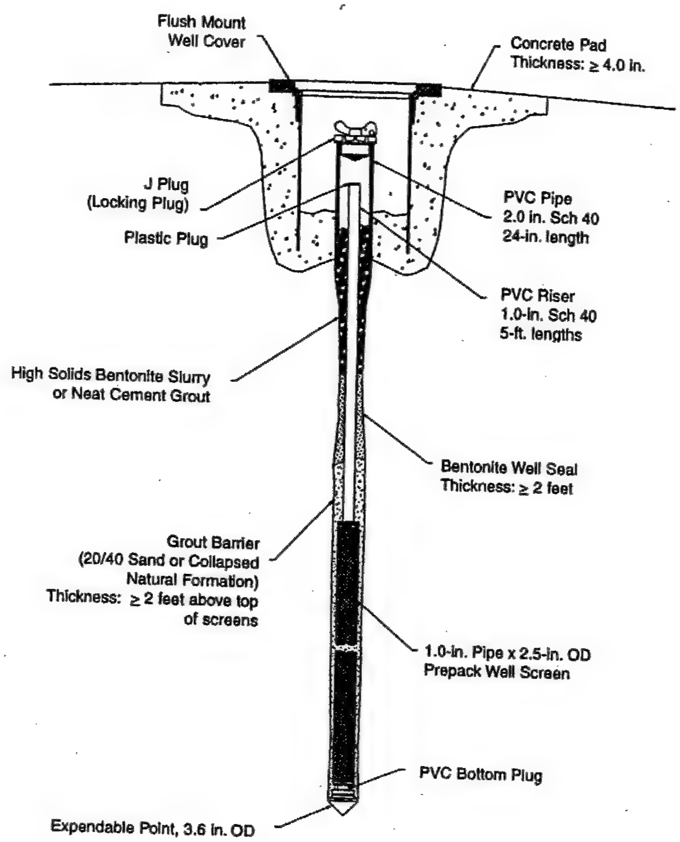

Figure 7. Illustration of a Finished Well Installation with Surface Seal

2.2 Strengths, Advantages, and Weaknesses

Installing monitoring wells by conventional methods is typically a time consuming and costly component of site characterization and monitoring. It is becoming widely recognized that direct push installation technologies are less costly than conventional approaches to well installation. In most formations, DP is minimally intrusive and causes less disturbance of the natural formation than many conventional drilling techniques. DP methods are rapid and economical, and smaller equipment with easier access to many locations can often be used. Worker exposure and investigative derived waste (IDW) disposal costs are reduced because little or no potentially contaminated drill cuttings are

generated when wells are installed with direct push methods. Since many DP wells have a smaller diameter than traditional wells, purge water volumes, sampling time, and indirect waste disposal costs are reduced for most sampling activities. Numerous innovations have been developed for groundwater monitoring through the direct push casings. For example, multiple screened sections can be completed in one installation, and using packers or sampling ports, groundwater sampling from multiple zones can be conducted.

However, the installation of DP wells is limited to unconsolidated soils and sediments including clays, silts, sands, and some gravels and cobbles, depending on the push equipment (e.g., heavy CPT trucks can push through harder materials than light trailer rigs). Direct push methods cannot be used to install monitoring devices in consolidated bedrock and deposits containing significant cobbles and boulders, or in heavily cemented materials. Also, smaller diameter screens and risers do not allow for use of some conventional down-hole pumps for purging or sampling. However, appropriately sized equipment is available and was used in this study.

2.3 Factors Influencing Cost and Performance

The primary factors influencing costs associated with the installation of either DP or conventional wells is directly related to the generation of solid and liquid IDW (Kram, 2001). Drilling spoils are essentially non-existent for DP wells with the exception of a small amount of soil removed while installing the surface seal and Christy box. Conversely, conventional well installations typically generate a significant volume of soil cuttings. For example, during the installation of the conventional wells at the Port Hueneme site approximately 40 gallons of waste were generated for each conventional well installed to a depth of 20 feet bgs.

From an operational standpoint, the smaller diameter (e.g., <1 inch) of some of the DP well styles limits their performance. The widely mandated low-stress (low-flow) sampling protocol for volatile organic compounds specifies drawdown limits within the well. If the limits are exceeded, it is assumed that the aquifer has been unacceptably stressed. Since well production for a given drawdown is proportional to the square of the well diameter, smaller diameter DP wells (microwells) often cannot conform to the requirements of this protocol without incurring prohibitively long purge times (i.e., requiring extremely low flow rates to stay within drawdown limits). Otherwise, it is assumed that the performance of DP wells is the same as conventionally drilled wells. Of course, it is the purpose of this project to demonstrate that fact.

3. Site/Facility Description

3.1 Background

The five sites chosen for this study were selected to satisfy several criteria:

- **To represent a variety of contaminants and geologic conditions**. These sites offered a broad range of common groundwater pollutants (BTEX, chlorinated solvents, MTBE) and geological settings ranging from shallow, homogenous sand

aquifers to deep, heterogeneous glacial deposits. Representing a variety of conditions was previously identified as a key factor needed to help promote acceptance of the study results. The specific contaminants and geologic features of each site are discussed in greater detail in Appendices B through F.

- **To represent a cross-section of regulatory domains.** The sites are located in five separate states and four EPA regions. Since one of the primary objectives was to promote broad regulatory acceptance of DP wells for long-term monitoring, material participation in the study by regulators was both desirable and necessary, and was solicited as part of this project.
- **For proximity to study team members.** This consideration allowed direct participation and oversight by team members in field activities without incurring unnecessarily burdensome travel and coordination expenses. Three of the five sites were co-located with team member's duty stations. CRREL is within a 40-minute drive of ARA's New England Facilities, Hanscom AFB is within 3 hours drive of CRREL and ARA, and DNTS is under the management of AFRL, which maintains staff on site who helped coordinate and perform field activities there.
- **To leverage experimental apparatus and sampling support provided by other studies, past and present.** A prior study by AFRL to assess DP well performance established 43 DP wells adjacent, and nearly identical in construction detail, to conventionally drilled wells at Hanscom AFB. Eight of these existing well pairs were selected for use in the study. A concurrent study by NFESC at Port Hueneme required the installation of eight multiple-well clusters, which was also used for this project. The Navy leveraged funds to cover all sampling costs at their site, and DNTS did the same at Dover AFB. The selection of Tyndall AFB allowed Air Force team members at the site to perform sampling with significant cost savings.

3.2 Well Selection Criteria

It was critical to the success of this project to ensure that the conventional wells were chosen to meet the characteristics listed in Table 1 to the greatest extent practical.

Table 1. Well Selection Criteria

CRITERIA	DESIRED CHARACTERISTICS
Hydraulic conductivity	Moderate values (~ 0.1-1 ft/day) preferred, no strong gradients
Geology	Homogeneous within the screened interval
Well inner diameter	2" i.d. preferred, others acceptable if no alternatives available
Well material	Sch 80 PVC is preferred, but Sch 40 is also acceptable
Screen slot size	10 slot is preferred, but 20 slot is acceptable if the DP well is the same
Contaminant types	Refer to the 13 contaminants listed in Section 1.2
Contaminant Concentrations	~ 100-1000 ppb is best, slightly higher acceptable, no strong gradients
Free product	No free product or NAPL is acceptable
Historical records	Some record of consistent concentrations over several years is preferred
Water quality	No extreme conditions (pH, Eh, etc.) that could affect lab analyses
Obstructions	No surface or subsurface obstructions; room for concrete well pad

3.3 Site/Facility Characteristics

The demonstration sites, and some general hydrogeologic and contaminant characteristics are shown in Table 2. Pairs or clusters of direct push (DP) wells and conventionally drilled wells were established at each of the sites. "Primary Well Pairs" refers to the number of conventional wells at each site that were paired with a similar sized DP well. "Secondary wells" refers to the number of microwells (1" or smaller i.d.) that were also installed at each site.

Table 2. General Test Site Characteristics

Location	Primary Well Pairs	Secondary Wells	Geologic Character	Depth to GW (ft)	Potential Analytes	Max Analyte Concentration (ppb)
CRREL	3	0	Glaciofluvial & Glaciolacustrine	87 - 128	Chloroethenes	124,000
DNTS	6	0	Marine Depositional	15 - 26	Chloroethenes, MTBE, Chlorobenzenes, DCA	4236 143
NFESC	8	16	Fluvial Deltaic	5 - 12	MTBE	280
HAFB	8	0	Glaciolacustrine	3 - 15	Chloroethenes, BTEX, Chlorobenzenes	393
TAFB	8	16	Marine Depositional	3 - 8	TCE, DCE, VC, BTEX	9.6; 3; 63; 25,000

Individual site histories, characteristics, maps, illustrations and other site-specific details are provided in Appendix B.

4. Demonstration Approach

4.1 Performance Objectives

The performance objective of this study was to demonstrate that the results of monitoring groundwater using DP wells agrees with results obtained using the accepted baseline of conventionally drilled wells for long-term monitoring.

A caveat of this approach is that comparing direct push installed wells to conventionally drilled wells with the intent to determine their validity implies that the conventional wells produce empirically, or absolutely accurate monitoring results. In reality, there is no universally accepted standard monitoring well or sampling method that produces absolutely accurate representation of the groundwater. This is important because the primary focus of this study is not to measure the accuracy with which samples from DP wells are representative of the groundwater, but rather to determining whether DP wells produce the same results, statistically, as conventionally drilled wells.

In such a comparison, due to influences on the observations made which cannot be completely controlled, there is no absolute indication of sameness. Instead, the performance objective must be expressed in terms of the maximum acceptable degree of statistical uncertainty that sameness must exist. For this study, the performance objective is acceptance of the null hypothesis that the results from the two wells do not differ at the 90% confidence level (α=0.05 for a two-tailed test). That is, a p-value of greater than 0.05 would indicate success. In other words, if we can not reject the null hypothesis with

better than 90% confidence, we must conclude there is no statistically significant bias introduced by substituting DP wells for conventional wells for ground water monitoring.

4.2 Physical Description and Operation

Following are general descriptions for drilled monitoring well installations, DP monitoring well installations, and groundwater sample collection procedures. These three topics constitute the areas of emphasis for this comparison. While additional technologies were used in this project (cone penetrometer testing, etc.), the purpose of this section is to describe similarities and differences inherent in the well installation and sampling approaches used.

4.2.1. Drilled Well Installations

Although pre-existing conventional wells were used at all of the sites with the exception of Port Hueneme, a discussion of typical installation procedures is included for comparison with direct push well installations.

Typically, a hollow stem auger drilling method is used to install conventional monitoring wells. A stable 6 to 12-inch diameter borehole, depending on the auger size used, will be constructed prior to installation of the 2-inch diameter well screen and riser pipe. All well screen and riser materials are certified clean from the manufacturer and care is taken to avoid contamination during handling. The well screen and riser assembly is set into the central guides along the stem of the auger flights. The field geologist determines screen lengths and any well customization requirements prior to drilling. The volume of filter pack required to fill the annular space between the well screen and borehole is computed, measured, and recorded on the well completion diagram during installation. Placement of the well screen is preceded by placing no less than 2% and no more than 10% of the primary filter pack into the bottom of the borehole using a decontaminated, flush threaded, 1-inch (25-mm) minimum diameter tremie pipe. The remaining filter pack is then placed in increments as the augers are gradually raised. A weighted line inserted through the tremie pipe is used to measure the top of the filter pack as work progresses. Care is taken to avoid bridging. The elevation, volume and gradation of filter pack material were recorded on the well completion diagram. The hollow stem auger is withdrawn in stipulated increments. Care is taken to minimize lifting of the riser as the auger flights are withdrawn. To limit borehole collapse, the augers are withdrawn until the lower-most point is at least 2 feet (0.6-m), but no more than 5 feet (1.5-m) above the filter pack. A bentonite seal is placed in the annulus between the borehole and the riser pipe on top of the filter pack by use of a tremie pipe. Sufficient time is allowed for bentonite hydration and expansion prior to grouting the remaining annulus. The volume and elevation of the bentonite seal material is measured and recorded on the well completion diagram. A protective access cover was sealed and immobilized in concrete at the ground surface. The concrete pad is sloped to promote water drainage away from the well. The top of the riser pipe is typically notched and surveyed so that measured water levels will maintain a constant location (vertical and horizontal) reference. Labels on the vault lids identify the well. Wells are customized based on the future monitoring requirements. For example, screens many be installed at multiple depths if shallow and deep samples are to be used to monitor the chemical stratification of a dissolved plume.

Well screen depth ranges are sometimes dictated by the results from the grain size distribution and corresponding hydraulic conductivity data.

4.2.2. DP Well Installations - Exposed Screen Wells

Due to their ability to closely match the construction details of conventionally drilled wells, thus limiting extraneous influences on observed performance, DP wells of the exposed screen type were the primary DP well type for this study. This type of well, fully described in Section 2.1, was installed adjacent to conventionally drilled wells at each demonstration site (with the exception of CRREL) according to standard installation procedures developed by ARA. This method closely follows the methods adopted in the new ASTM method developed as a separate task under this project.

Wells were constructed of 2-inch diameter schedule 80 PVC with flush threaded joints. Each section measured one meter (3.28 feet) in length (shoulder to shoulder), with an outside diameter of 2.375 inches. Where possible, the well screen matched the slot size of the conventionally drilled well with which it was paired, and was configured to match as closely as possible the screen top and bottom elevations of the conventionally installed well. For some existing DP wells, installed under the previous project at Hanscom AFB, a 0.020-inch slot schedule 80 PVC was used where 0.010-inch existed for the conventional wells. There were other minor differences in the construction of two well types at Hanscom, which have been noted.

Exposed screen DP wells were installed by threading a sacrificial stainless steel or high-strength plastic tip, which acts as the drive point, into one end of a one-meter silt trap section (solid riser). The screen sections were threaded on to the silt trap then advanced into the ground by the CPT rods bearing on the sacrificial tip under static hydraulic force. Sufficient (1-meter) rod sections were added so that the end of the rods extended beyond the top of the well material and the head clamp could clamp the rods and not the well material. Installation began as the rods drove the sacrificial tip into the ground, pulling the well material into the ground behind it. Additional screen and riser sections were subsequently added as necessary until the screen section was at the desired depth, matching the depth of the pre-existing conventional well.

At this point, the rods were removed from the well and a depth indicator is lowered down the well to verify the total depth. This information was recorded on the well installation logs. Upon removal of the rods, the rods were decontaminated using the CPT rig's steam cleaner.

All of the direct push wells at the Dover AFB site and some of the wells installed at the Tyndall sites were of the exposed screen type and were installed using a CPT type rig. Six, 2-inch diameter direct push wells were installed at Dover using the DNTS's trailer mounted CPT rig. At Tyndall, the US Army Corps of Engineers installed eight, 1-1/2 inch diameter direct push wells using their CPT rig. Well construction details for these wells are included in Appendix C.

4.2.3. DP Well Installations - Pre-packed Wells

In addition to the primary DP well type described above, some sites utilized pre-packed DP wells and microwells for additional comparisons. These types of wells are more commonly used for site investigation and monitoring work, and have the advantage of the sand filter pack preinstalled around the well screen. This allows the pre-packed well to be designed to conform more closely to ASTM guidelines.

Under the direct supervision of Mr. Wesley McCall, Geoprobe Systems® (a division of Kejr, Inc., Salina, KS) installed all pre-packed direct push wells at both the Tyndall and CRREL sites. Sixteen additional wells (eight ½-inch diameter, and eight 1.0-inch diameter) were installed at the Tyndall site utilizing a percussion style direct push rig. Table 3 summarizes the details of these installations. Three ½-inch diameter pre-packed wells were installed at CRREL adjacent to previously installed 4-inch diameter conventional monitoring wells. Summary reports detailing the Geoprobe rigs, associated equipment and installation procedures employed to install these wells are included in Appendix C.

Table 3. Details of DP wells with pre-packed screened sections installed at Tyndall AFB.

Well Number	Location (Tyndall AFB, FL)	Date Installed	Nominal Well ID (inches)	Total Depth of Boring (ft)	Screen Interval (ft)	Development Water (~gallons)
DPW2-MW1	MW1, SS026, SW side Alabama Ave.	8/8/00	1.0	14.0	3 to 13	NA
DPW3-MW1	MW1, SS026, SW side Alabama Ave.	8/9/00	0.5	13.5	4 to 13	NA
DPW2-MW2	MW2, across Florida Ave. from SS015	8/7-8/00	1.0	37.0	26 to 36	110
DPW3-MW2	MW2, across Florida Ave. from SS015	8/8/00	0.5	36.5	27 to 36	45
DPW2-MW5	MW5, SA150, near Flight Ops. Bldg.	8/9/00	1.0	12.5	1.5 to 11.5	35
DPW3-MW5	MW5, SA150, near Flight Ops. Bldg.	8/9/00	0.5	12.0	2.5 to 11.5	30
DPW2-T6-5	T6-5, South of fire training area on access road near Highway 98	8/10/00	1.0	20.0	4 to 19	60
DPW3-T6-5	T6-5, South of fire training area on access road near Highway 98	8/10/00	0.5	19.5	4 to 19	40
DPW2-MW8	MW8, SA150, near Flight Ops. Bldg.	8/9/00	1.0	12.5	1.5 to 11.5	35
DPW3-MW8	MW8, SA150, near Flight Ops. Bldg.	8/9/00	0.5	12.0	2.5 to 11.5	35
DPW2-MW9	MW9, SS015, between Florida and Alabama Ave.	8/8/00	1.0	13.5	2.6 to 11.6	55
DPW3-MW9	MW9, SS015, between Florida and Alabama Ave.	8/8/00	0.5	13.3	3.8 to 12.8	40
DPW2-MWD9	MWD9, behind base service sta. off of Illinois Ave.	8/10/00	1.0	29.5	3.4 to 28.4	NA

Well Number	Location (Tyndall AFB, FL)	Date Installed	Nominal Well ID (inches)	Total Depth of Boring (ft)	Screen Interval (ft)	Development Water (~gallons)
DPW3-MWD9	MWD9, behind base service sta. off of Illinois Ave.	8/10/00	0.5	28.9	4.4 to 28.4	NA
DPW2-MWD11	MWD11, behind base service sta. off of Illinois Ave.	8/10/00	1.0	29.5	3.5 to 28.5	NA
DPW3-MWD11	MWD11, behind base service sta. off of Illinois Ave.	8/10/00	0.5	28.9	4.4 to 28.4	NA

Table 4. Details of DP wells with pre-packed screened sections installed at CRREL.

Well Number	Location (CRREL)	Date	Nominal Well ID (inches)	Total Depth of Boring (ft)	Screen Interval (ft)	Development Water (gallons) and Final pH	Time for Casing Advancement	Time for Well Installation & Grouting
DP-11	MW-11	9/22,23 & 25/00	0.5	116.0	105.5 to 114.5	12 gal. pH = 5.4	16.5 hrs* (2.125" x 3.25" rods)	4 hrs
DP-10	MW-10	9/25/00	0.5	128.0	117.5 to 126.5	7.5 gal. pH = 5.6	65 min. (2.125" rods)	3 hrs
DP-09	MW-09	9/26/00	0.5	138.5	129 to 138	6.5 gal. pH = 5.5	80 min. (2.125"rods)	2 hrs

4.2.4. Surface Seal

After each well was installed, a flush-mounted protective access cover was sealed and immobilized in concrete at the ground surface. The concrete pad was sloped to promote water drainage away from the well. The tops of the riser pipe were notched and surveyed so that measured water levels are referenced to a constant vertical datum. Labels attached to the vault lids clearly identified the well ID.

4.2.5. Well Development

All newly installed wells were developed using mechanical surging and pumping in accordance with ASTM 5521. Development continued until representative water (based on stabilized pH, temperature, dissolved oxygen, ORP or redox potential, specific conductivity and turbidity) was obtained. The results of water quality monitoring and the duration of well development activities were recorded on separate Well Development Logs for each well.

4.2.6. Slug Tests

In an effort to identify the influence of the different well geometries and installation techniques on the apparent hydraulic conductivity of the formation as measured via a well, slug tests were conducted on one well cluster (five wells) at the NFESC site in Port Hueneme, CA. A series of seven slug tests were conducted and analyzed. The data obtained was used to determine the influence of well style and installation technique on the magnitude (mean) and repeatability (variance) of the measured hydraulic conductivity. Any differences that correlated to well type were also used in the interpretation of inter-well differences in the chemical concentration data.

Slug tests induce a sudden change in head in a well, and then measure the water level response within that same well. For this study, head change was induced by pressurizing the water column, effectively depressing it, then suddenly releasing the pressure and observing the water-level response in the well as a function of time. Water level data was recorded with a down-hole piezoresistive pressure transducer connected to a data logger. Data was logged at logarithmically increasing time intervals to accurately define the time versus hydraulic head curve. The slug tests were conducted in accordance with ASTM D 4044-96 and the data was interpreted using the Bouwer-Rice (1976) technique.

The Bouwer-Rice solution assumes the following[1]:

- Unconfined or leaky-confined aquifer (with vertical drainage from above) of "apparently" infinite extent,
- Homogenous, isotropic aquifer of uniform thickness,
- Water table is horizontal prior to the test,
- Instantaneous change in head at start of test,
- Inertia of water column in head at start of test,
- Fully or partially penetrating well,
- The well storage is not negligible, thus it is taken into account,
- The flow to the well is steady state,
- There is no flow above the water table.

The data requirements for the Bouwer-Rice solution are:

- Drawdown / recovery vs. time data at a well,
- Observations beginning from time zero onward (the value recorded at $t = 0$ is used as the initial displacement value, H_0, and thus must be a non-zero value).

Figure 8 illustrates the mechanics and geometry of a slug test conducted using the Bouwer-Rice solution.

[1] Aquifer Test v.3.0 Reference Manual, pp. 41-44. Waterloo Hydrogeologic, Waterloo, Ontario, Canada.

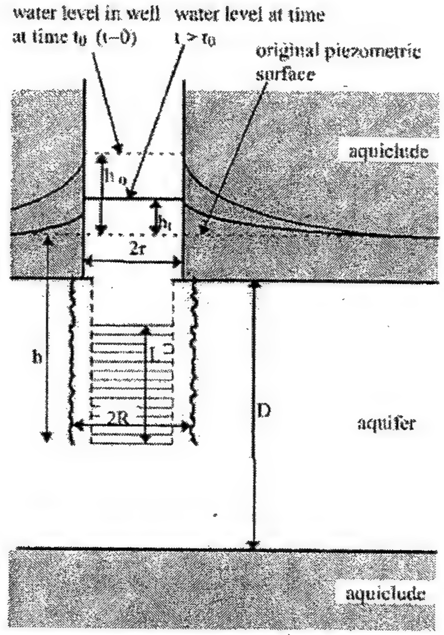

Figure 8. Geometry and Mechanics of a slug test conducted using the Bouwer-Rice solution. (Source: Aquifer Test v.3.0 Reference Manual, Waterloo Hydrogeologic, Waterloo, Ontario, Canada).

4.3 Sampling Procedures.

In this study, DP wells were installed alongside, and as close as practical, to existing conventionally drilled wells at five demonstration sites. Pairs and clusters of wells were sampled to generate paired data for comparing the performance of different well types in a rigorous statistical fashion. Five rounds of groundwater samples were taken from each well pair or cluster in the study at each demonstration site, at approximate quarter-annual intervals. All wells were sampled in accordance with the approved Work Plan (Appendix B)

Since the comparison of the demonstration technology to baseline technology must be done by obtaining pairs of independent random samples under identical conditions, it was necessary to ensure by examination of historic groundwater monitoring data and trend analysis, that well locations were chosen such that a reasonable range of contaminant concentration observations were present over the life of the project. This ensured that a sufficient number of independent random samples (i.e., degrees of freedom) were present in the sample set for analysis. Typical situations that were screened out include:

- Well pairs that were installed in the vicinity of very high concentrations. High concentrations of only some analytes in a matrix may require samples to be diluted for analysis, which would force concentrations of other contaminants below analytical method detection limits for the diluted samples.
- In regions of high concentration gradients, observed water quality differences between paired wells may be due to actual differences occurring over the distance between the wells, rather than as an effect of the installation method.

- If well pairs were located in areas of very low concentration, approaching analytical detection limits, non-detects would be prevalent, which makes statistical comparisons more difficult and diminishes the power of the statistical tests.
- Large separation distance between the conventional and DP wells. There was no set value specified in the protocol for the recommended distance between the wells. Instead, site managers used the following two criteria to decide how closely the wells could be positioned: (1) they should not be so close that the radius of influence of the purges overlap, and (2) the DP well should be far enough away from the conventional well so that there was no danger of impinging the conventional well filter pack due to a wandering (e.g. deflected) push string during installation. The second factor was of concern only on deeper well installations, such as at CRREL, because a rod deflection of only a couple of degrees can cause a displacement of several feet at those well screen depths (e.g., approximately 130-ft below grade). Generally, as close to the conventional well as the DP rig could be positioned, leaving room for the required concrete well pad, was considered far enough away to safeguard against both these issues.

4.3.1. Sample Collection

There are many different procedures currently in practice for sampling programs. The needs and objectives of the program often dictate the type of sampling method. The objectives of this sampling program were to collect water samples from wells where the constituents of concern included volatile organic compounds. Additionally, since the study was an experiment to support and validate the use of CPT-installed wells, the scientific and regulatory community must ultimately support the sampling procedure. To meet these criteria, a low-stress (low-flow) purging and sampling procedure was implemented. A protocol for this technique, published in EPA/540/S-95/504, Low-Flow (Minimal Drawdown) Ground-Water Sampling Procedures, dated April 1996, by Puls and Barcelona, was recommended by US EPA Region 1. This document is included for reference in the Work Plan (Appendix B), and served as the procedural guide for sampling.

4.3.1.1. Sampling Method

Samples were collected using peristaltic pumps with dedicated tubing from wells where the ambient potentiometric surface was shallower than twenty-six feet. From wells where the water surface was deeper than twenty-eight feet, samples were collected using bladder pumps, stainless steel Grundfos Redi-flow™ submersible pumps, or other pump accepted by the specified method. Field water quality parameters were measured using a YSI Model 6820, Hydrolab, or comparable device with a flow-through cell. Instrument specifications and calibration procedures for the instruments employed are documented in the project work plan (Appendix B). The same monitoring device was used consistently at each well pair or cluster throughout all sampling rounds.

Prior to collection of groundwater samples, each well was purged until field measurements of pH, temperature, dissolved oxygen, ORP or redox potential, specific

conductivity and turbidity stabilized. Field parameters were recorded at regular intervals (at least once per well volume) with the specified instrument using a flow-through cell. This instrument was calibrated at the start of each sampling day and after extended periods of non-use. If any free product passed through the flow-through cell, this cell, tubing, and all sensors were thoroughly cleaned and recalibrated according to the manufacturers recommendations before further use.

Oxidation-reduction potential was reported referenced to the hydrogen electrode and was calculated as specified in ASTM D-1498:

$$E_h = E_{obs} + E_{ref} \tag{1}$$

where:

E_h = oxidation-reduction potential referenced to the hydrogen scale, mV

E_{obs} = observed oxidation-reduction potential of the noble metal-reference electrode employed, mV

E_{ref} = oxidation-reduction potential of the reference electrode as related to the hydrogen electrode, mV

Other details associated with the sampling methods are discussed in detail in the Work Plan included as Appendix B.

4.3.1.2. Sampling Equipment Decontamination

All sampling equipment was decontaminated before the beginning of each sampling round and after each well was sampled. Decontamination of the equipment reduced the risk of worker exposure, reduced the risk of cross contamination and insured collection of representative samples. The procedure summarized below is detailed in the Work Plan in Appendix B.

If dedicated tubing was not used, the outside of the sampling tubing was decontaminated during retraction of the sampling pump. When the pump has been removed from the well it was placed in a water and Liquinox™ bath. Three pump volumes were pumped through the pump and sampling tubing (if non-dedicated). This process was repeated for two baths of tap water rinse and again in a bath of reagent free water.

4.3.1.3. Sample Containers

Each sample was collected in a 40-ml glass vial with Teflon-backed septum. Sample vials were pre-cleaned and suitable for purgeable volatile organic analysis (PVOA).

Sample containers were filled such that no air was retained within the sample vial. The absence of headspace was verified by turning the capped vial upside-down and tapping the lid while watching for bubbles. Sample labels with requisite identification data were affixed to each vial. All sample vials were placed into foam blocks for protection during shipment, and each block was enclosed within a single plastic bag. Filled sample vials

were stored at four degrees centigrade in a refrigerator or placed on ice in an insulated cooler until delivery to the analytical laboratory.

4.3.1.4. Sample Identification

Field samples and associated QA/QC samples were labeled with the date and time of collection, sampling personnel's initials, well ID and depth, and a unique sequence number. The same information was recorded in the field on the sampling logs.

4.3.1.5. Sample Preservation

Samples were preserved with hydrochloric acid (HCl). Water at the site was tested to determine how many drops were required to increase the acidity to pH2. The appropriate number of drops was then added to each sample.

Samples analyzed by the certified laboratory were packed into a separate cooler at the end of the sampling day. A Chain-of-Custody Form was signed and placed in a re-sealable plastic bag within the cooler and the cooler was sealed with tape and a Chain-of-Custody Seal, such that the seal would necessarily be destroyed before accessing the cooler. The coolers were shipped to the laboratory by overnight express (or equivalent) mail from the field.

Allowable holding times for samples sent to both AFRL's laboratory or the QA/QC laboratory was 14 days.

4.3.1.6. Chain-of-Custody Records

Chain-of-Custody Forms accompanied all samples delivered to each laboratory. The forms listed the number of vials of each size contained in each cooler. They were signed and dated by field personnel at the time of packing for shipment from the field, and by laboratory personnel at the time of receipt in the laboratory. An example Chain-of-Custody Form is provided in the Work Plan.

4.3.2. Experimental Controls

The power of the statistical tests for comparing the two well installation methods is dependent on the minimization of potential extraneous factors. An extraneous factor is anything besides the installation method that may induce variability either: (1) across independent sampling events from any one well type, or (2) between the two well types during any given sampling event. Extraneous factors of the first category include:

- defects in existing or new well construction (e.g., leaky seals, cracked casings, etc.)
- variability in sampling or analysis technique
- variability in groundwater flow direction, velocity, or contaminant source loading

Extraneous factors of the second type include all of the above, plus:

- variations in well materials

- differences in well screened interval (depth and length)
- differences in well diameter (due to impact on flow characteristics)
- differences in well slot size (due to impact on flow characteristics)
- study-induced differences (e.g., purge sequence effects)

Extraneous factors of the second type are suppressed by:

- matching materials between existing and new wells
- matching screened intervals of new (DP) wells to those of existing (auger drilled) wells as closely as practicable
- matching well diameters and slot sizes as closely as practicable
- orienting matched pairs along an axis of low concentration gradient (e.g., the line segment drawn between two paired wells should be parallel to the local concentration isopleths)
- randomizing the sampling sequence (e.g. alternating between "direct push first" and "auger drilled first," upgradient/downgradient, etc.)
- Extraneous factors of the first type are suppressed by:
- conducting statistical analyses on wells in pairs (e.g., Wilcoxon Matched Pairs Signed Rank test, Matched Pairs t test)
- installing the new (direct push) well as near as practicable to the existing (auger drilled) well with which it is paired
- strict adherence to well installation protocols (repeatability).
- strict adherence to sampling and analytical protocols (repeatability)
- pre-screening existing wells (or pairs) to exclude those which show a high degree of variability across independent sampling events (i.e., non-repeatability)

Additionally, a historical review of existing groundwater contaminant distribution and hydrogeologic data was performed, when such data was available, during the well selection process to avoid to the greatest extent possible any areas with the following characteristics: (1) high concentration gradients, (2) areas with consolidated materials (e.g., rock and gravel), (3) areas with any DNAPL pool or LNAPL distribution, and (4) areas with steep potentiometric surfaces.

Lack of adequate suppression of any of the listed extraneous factors can lead to greater variability in the intra-well and paired differences of groundwater monitoring data obtained. Such variability diminishes the value of the statistical analyses, and thus necessitates a greater number of independent samples to achieve the same level of *confidence* and *power* in the resulting comparison.

The study was designed to take advantage of every opportunity to suppress extraneous factors. Regulatory approved and standardized protocols for well installation and development, groundwater sampling, and laboratory analytical methods were specified and adhered to as much as possible. The Quality Assurance Project Plan (QAPP) found in section 9 of the Work Plan (Appendix B) details the process by which adherence to the work plan was assured and documented.

4.4 Analytical Procedures.

4.4.1. Selection of Analytical Laboratories

The primary analytical lab for performing analyses of the groundwater samples collected during this project was AFRL/MLQL (Air Force Research Laboratory, Air Expeditionary Forces Technologies Division, Weapons Systems Logistics Branch) located at Tyndall AFB, FL.

Severn-Trent Laboratories (STL, Colchester, VT) was selected as the contract analytical lab for the 20% QA samples of VOCs in groundwater. The selection criteria consisted of participation in the EPA Contract Laboratory Program, prior reputation with the project team, and cost. STL obtained a score of 100% in a recent double blind performance evaluation by Analytical Standards, Inc. STL's EPA CLP number is VT00008. Their Vermont State Department of Health identification number is VT-4000.

Lancaster Laboratory (Lancaster, PA) was selected as the as the analytical lab for the inorganic analyses under subcontract to NFESC via Bechtel government services. They were selected based on proven performance on previous contracts to NFESC and acceptable cost.

4.4.2. Selection of Analytical Method

The analytical method for monitoring volatile organic compounds (VOCs) was selected based on feedback from the regulatory community and in consideration of the relevance of the anticipated results to long-term regulatory monitoring. Standard EPA methods specified in *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846, 3rd Edition* (USEPA, 1996) were identified as the most appropriate analytical methods for evaluating VOCs in groundwater for this study. Calibrated field monitoring devices, as described in the sampling protocol and QA Plan, were used to analyze water quality parameters monitored during well purging. Methods for evaluating inorganic species were selected to match the parameter list developed by NFESC on a previous project thereby yielding a larger dataset for analysis.

4.4.3. Sample Analysis

Chemical analysis of samples was performed at AFRL's laboratory for selected compounds using EPA SW-846 methods, including method 5030 purge and trap for sample extraction and modified EPA method 8021B for the analysis of volatile organic compounds in water. Modifications to method 8021B included the use of a capillary column in place of a packed column and truncation of the standard analyte list. The truncated target analyte list included only the purgeable halocarbons, aromatics, and MTBE as presented in Table 5.

Split samples for laboratory Quality Assurance/Quality Control (QA/QC) were sent to Severn-Trent Laboratories (STL, Colchester, Vermont). Analysis of splits were performed using Gas Chromatography/Mass Spectrometry (GC/MS) following EPA Method 8260 with the same modified analyte list presented in Table 5.

Table 5. Volatile Organic Analyte List

Analyte	Sites Where Analytes Were Present
perchloroethene	Hanscom AFB, Tyndall AFB, DNTS
trichloroethene	CRREL, Hanscom AFB, Tyndall AFB, DNTS
cis-1,2-dichloroethene	CRREL, Hanscom AFB, Tyndall AFB, DNTS
trans-1,2-dichloroethene	Hanscom AFB, Tyndall AFB, DNTS
vinyl chloride	CRREL, Hanscom AFB, Tyndall AFB, DNTS
benzene	Hanscom AFB, Tyndall AFB, DNTS
toluene	Hanscom AFB, Tyndall AFB, DNTS
ethylbenzene	Hanscom AFB, Tyndall AFB, DNTS
o,m-xylene	Hanscom AFB, Tyndall AFB
p-xylene	Hanscom AFB, Tyndall AFB
1,4-dichlorobenzene	Hanscom AFB, Tyndall AFB
trichloroethane	Hanscom AFB
MTBE	Port Hueneme, DNTS

5. Performance Assessment

5.1 Performance Data

5.1.1. Field Replicates (Split Samples)

Split samples were collected from up to twenty percent (20%) of the total number of samples. Split samples were collected from both the CPT installed wells and the conventionally installed wells. Splits were sent to a certified laboratory (STL) for analysis by EPA Method 8260 to evaluate the analytical performance of AFRL's laboratory. Splits were collected in the same manner as field duplicate groundwater samples. The results from the split samples provide a measure of the precision (repeatability) of the field sampling methods and help to add validity to the results from AFRL's laboratory. The results of the field replicates are discussed in Section 5.2 Data Assessment.

5.1.2. Trip Blanks and Field Equipment Blanks

Trip blanks were prepared in AFRL's and STL's laboratories using the same analyte-free reagent water used in the preparation of check standards and instrument blanks. They were delivered to each of the sites packaged with the empty sample containers and subsequently returned along with the filled sample containers. Equipment blanks were taken for each day of on-site sampling at sites not using dedicated sampling equipment. Equipment blanks were prepared in the field by passing analyte-free water through all

decontaminated sampling equipment in the same manner that a groundwater sample would pass. The use of equipment blanks validated the effectiveness of equipment decontamination procedures. Sites using dedicated tubing and peristaltic pumps were exempt from taking equipment blanks.

Trip blanks and equipment blanks were handled, transported, and analyzed using identical procedures as those used for regular groundwater samples. All criteria outlined in the Quality Assurance Project Plan (QAPP) with regards to the trip blanks and equipment blanks were met during the course of this project.

5.1.3. Matrix Spike and Matrix Spike Duplicate Samples

Field duplicate samples were collected for five percent (5%) of the total number of samples collected for the purposes of preparing Matrix Spikes (MS) and Matrix Spike Duplicates (MSD). Duplicates were collected by discharging from the same pump volume, first into the original sample container and then into the duplicate container. They were identified with the suffixes MS and MSD on the Chain-of-Custody Forms. These samples helped identify matrix effects on spiked analytes of known quantity, as well as the laboratory's precision in recognizing matrix effects. All MS and MSD criteria outlined in the Quality Assurance Project Plan (QAPP) were met during the course of this project.

5.2 Data Assessment

Data quality procedures outlined in the project QAPP, were strictly adhered to for both sampling and analysis. These procedures included EPA standard well sampling protocols and standard analytical methods.

Groundwater sampling was performed according to the low-stress sampling procedure (reference). All field procedures were documented and any deviations from the protocol were noted and later evaluated for their potential to impact data quality. No significant deviations were found to occur.

Primary analytical procedures for VOAs conformed to SW-846 standard 8021B. Quality controls on this standard included procedures for:

- Receiving, log-in, and storage of field samples;
- Chain-of-custody documentation;
- Standards preparation and analysis;
- Instrument calibration; and
- Instrumentation QC

The full requirements of the QAPP are contained in section 9.1 of the project workplan. These quality control and quality assurance measures were developed with the intent of producing appropriate and defensible data for the technology evaluation. They received extensive programmatic, regulatory, and peer review, and were adhered to throughout the project without exception, thus assuring that the data generated support a realistic assessment of the technology.

In addition to the internal laboratory procedures, a proportion of field samples were split and sent to a second laboratory for quality assurance. The QA laboratory, a participant in the EPA Contract Laboratory Program (CLP), provided level 3 reporting and analyzed the samples in compliance with SW-846 method 8260, a gas chromatography/mass spectrometry method for VOAs. Quality controls similar to those of the primary lab also applied to analyses conducted by the QA laboratory.

According to a study published by CRREL (Grant, Jenkins, Mudambi, 1996), it is recommended that ratios of primary laboratory result to QA laboratory result (QC/QA ratios) for VOCs in groundwater fall within the range of 0.4 to 2.5 (e.g., each within 2.5 times the other). These recommendations, derived from statistical analysis of archived results of USACE-directed environmental studies, are applicable where the two laboratories employed identical analytical protocols. The guidance admits an expectation that some proportion of QC/QA ratios will exceed the bounding criteria. In fact, in the CRREL study itself, 5.6% of VOCs in groundwater were found to exceed the suggested criteria.

In the current study, 17% of the QC/QA ratios exceeded the recommended identical method range. However, given that the two laboratories in the current study employed different analytical methods, a more reasonable range of QC/QA ratios to expect would be 0.2 to 5.0. This range was exceeded by only 9.3% of QC/QA ratios in the current study. Thus, the results are consistent with the published CRREL guidelines and provide additional assurance that the data generated support a realistic assessment of the technology.

5.3 Technology Comparison

Statistical tests of hypothesis were used to compare the performance of DP wells to that of HSA wells for groundwater monitoring. These tests were thoroughly explained in section 4.5.1 of the project workplan, and are summarized below.

5.3.1. Hypothesis Testing

Hypothesis testing was conducted on the differences between the samples collected from the DP wells and the samples collected from the conventionally installed wells. Paired-sample statistics were used for the testing. Paired tests are well suited for comparing the influence of a single factor (e.g. well installation method) in situations where the individual data are also subject to the influence of extraneous factors (e.g. contaminant concentration, geochemistry, hydrologic regime, screened interval, well construction details, etc.). In these cases, taking the data in pairs minimizes the variation due to extraneous factors, because the external influence may vary from pair to pair but is assumed to be the same within each pair.

In a test of hypothesis, two hypotheses are involved. They are statements about a population, which are tested by examining a sample of that population. The analyses conducted under this study tested the *null hypothesis*, that the mean of the population of differences within matched pairs of DP wells and HSA wells was equal to zero. The null hypothesis was evaluated against the *alternative hypothesis* that the mean difference is

greater than or less than zero. On the basis of the random sample from the population, one decides whether to accept or reject the null hypothesis.

Both parametric and non-parametric tests exist for the purpose of hypothesis testing, and the applicability of each type depends on the distribution of the population, as inferred from the distribution of the random sample obtained.

The Student t-test is a parametric test of paired data used to test hypotheses about the mean of a population. The Wilcoxon Signed Rank Test, also known as the Wilcoxon Matched Pairs Test is a non-parametric tests for this purpose.

The Student T Test is only applicable to a population that is near normal or can be transformed to a normal distribution. This test was conducted on populations of paired data that are found to pass a test of normality, as described below. The assumption of normality (and of log-normality) of the paired differences was tested by application of the Ryan-Joiner test, which is similar to the Shapiro-Wilk test (Shapiro & Wilk, pp.591-611). In all hypothesis testing, pairs of analytical non-detects were not included in the set, reducing the degrees of freedom N by one for each tie discarded.

5.3.1.1. Confidence and Power

There are two ways of making an incorrect decision in hypothesis testing. In a *type I* error, the sample data reject the null hypothesis even though it is true. In this application, a type I error would result in improper rejection of DP wells. The level of significance, denoted by α, is the probability of a type I error. The *confidence* of the test is denoted by $1-\alpha$. In most applications of environmental regulatory concern, a confidence of 95% (α =0.05) is considered acceptable.

The *P-value* is the smallest significance (α) at which the null hypothesis can be rejected for the given random sample. That is, for the mean of paired differences in our sample, the p-value represents the probability that a non-zero result, if observed, is due to chance occurrence in sampling the populations. At the chosen 95% confidence level, any P-value in excess of 0.05 results in acceptance of the null hypothesis.

In a *type II* error, the data support acceptance of the null hypothesis even though it is false. A type II error would result in improper acceptance of DP wells when in fact they produced monitoring results that were different from conventional wells. The probability of a type II error is denoted β. *Power*, denoted by $1-\beta$ can be thought of in terms of the test's ability to detect a difference between DP and conventional well types from the sample should one really exist in the general population.

For sample of a given size, a desirable increase in confidence (decrease in α) is accompanied by an undesirable decrease in power (increase in β). In the experimental design for a test of hypothesis, one usually selects the maximum tolerable size of type I error, then designs the experiment to minimize the size of type II error by controlling the choice of N, the number of observations in the sample, based on an assumed population variance. In this study, N was limited not only by budget and time constraints, but also by uncertainty in whether or not concentrations of each analyte would be found above method detection limits in each of the wells sampled. Therefore, the power of the tests of

hypothesis was beyond control of the investigators. However, the power of each test was calculated and is presented below. Power calculations for parametric tests were performed using MiniTAB™ software. All power estimates were calculated as the power of a t test, assuming normally distributed differences or logs of differences, with the most appropriate assumption being based on the p-values of the normality tests. Specific recommendations for improving power appear in section 7 of this document.

5.3.1.2. Sample Independence

All the statistical methods described herein require the collection of a random sample of independent groundwater data from the population of matched DP and conventional wells. Multiple samples from a given pair are only independent, however, if no extraneous factor introduces some systematic bias in a well pair.

To illustrate this point, consider the limiting cases in which a sample of size N is composed of, in one instance, a single round of monitoring from N well pairs, and in the other instance, N rounds of monitoring from one well pair. In the first instance, if some extraneous factor introduces a systematic difference between monitoring results from the two well types in any given pair, a sufficiently large sample size will ensure that such differences will be randomly distributed with a mean of zero over the sample. In this case, extraneous factors such as these will affect the confidence and power of the test by increasing the sample variance; but they should not impose a net bias on the mean of differences.

In the second instance, however, if a physical condition exists which introduces a systematic difference between the results from the two well types; this difference would impose a systematic bias on the sample mean because the sign and relative magnitude of the difference would not be expected to vary from sample to sample.

Therefore, in combining data from multiple sampling rounds, the potential for systematic biasing due to physical differences between wells in a pair relative to any variation in the observed hydrogeologic structure was safeguarded against. To check for the presence of any potentially biasing extraneous factor, analyses of variance (ANOVAs) were conducted.

5.3.2. Handling of Non-Detects

Occasionally, analytical non-detects resulted. If using the parametric t test, pairs of two non-detects were dropped from the sample, reducing N accordingly. For pairs containing one non-detect, it was replaced by half the analytical detection limit. For the non-parametric Wilcoxon Signed Rank Test, pairs of two non-detects were dropped and N reduced accordingly. Pairs containing one non-detect were ranked according to the difference between the quantified result and half the detection limit.

5.3.3. Comparison of VOA Data

The hypothesis testing was performed on the VOA analytical data from all five rounds of sampling combined. At some sites (Tyndall AFB and Port Hueneme), well clusters were composed of a single HSA well and several configurations of DP wells. Due to the

potentially biasing effect of including a single observation multiple times, it would be inappropriate to include paired differences from several DP wells with a single HSA well in the same random sample for statistical tests of hypothesis. Therefore, separate tests of hypothesis were conducted for each analyte and each nominal DP well size paired with the corresponding HSA well, so no single measurement was used more than once in a given test sample. Tests were conducted for DP well sizes of 2.0, 1.5, 1.0, and 0.75 inches, each paired with the 2-inch diameter HSA well in the cluster.

The first step in hypothesis testing, represented by the floe chart in Figure 6, was to calculate differences by subtracting the HSA well result from the DP well result. Next, assumptions regarding the distributions of differences between results from paired wells were checked. The Ryan-Joiner test (similar to the Shapiro-Wilk test) was used to determine, at 95% confidence, whether or not each sample of differences was normally distributed. If a normal distribution was found, then a 1-sample t test was used to test the null hypothesis that the mean of the differences was equal to zero (H_0:μ=0) against the alternative hypothesis that the mean was not equal to zero (H_0:$\mu \neq 0$).

However, if a normal distribution was not found, then the differences of the logarithms of the results were calculated, and the test of normality was applied to these data. If the differences of the logarithms were found to be normally distributed, then the 1-sample t test was applied to the null hypothesis that the mean of the differences of the logs was equal to zero. In this case, since the null hypothesis was tested using the difference of logarithms, it was equivalent to testing that the ratio of the DP result to the HSA result was equal to one.

If neither the differences nor the differences of the logarithms of the analytical results were found to be normally distributed, then the nonparametric Wilcoxon signed rank test (also called the Wilcoxon matched pairs test) was applied to the differences, testing the null hypothesis that the median of the differences was equal to zero against the hypothesis that the median was not equal to zero.

The flow chart in Figure 9 shows the sequence of tests that were applied in the hypothesis testing methodology.

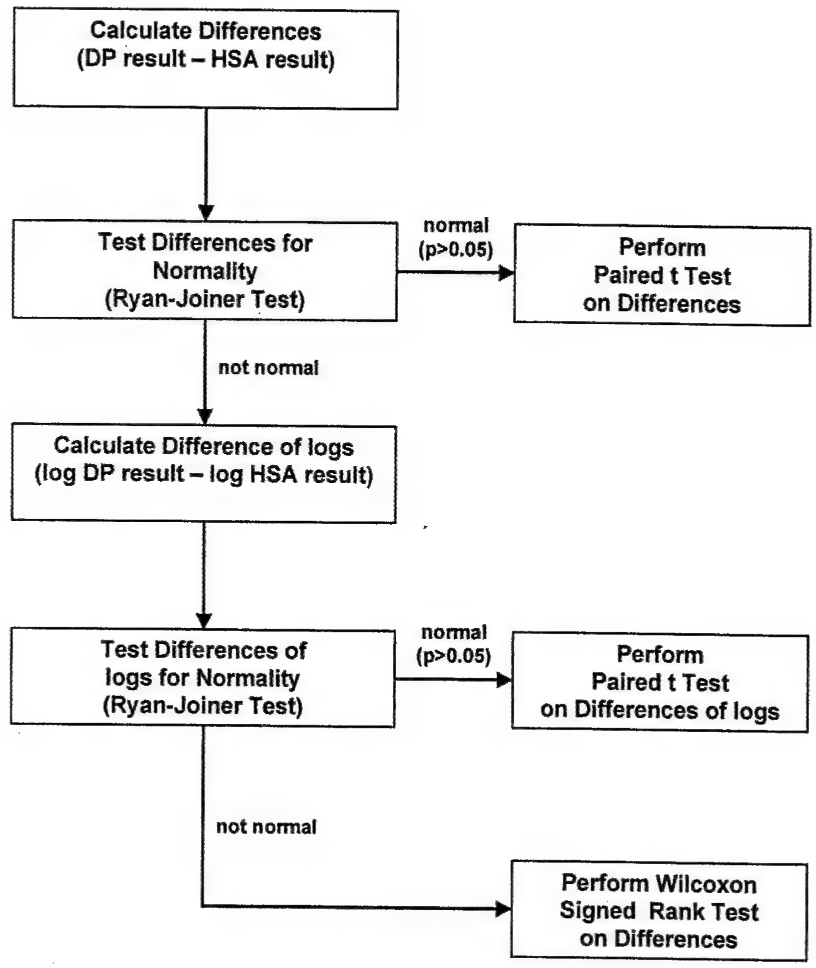

Figure 9. **Flow chart of process for statistical tests of hypothesis**

The results of the statistical testing are summarized in

Table 6 through Table 10. In every case in which the null hypothesis was rejected, both the mean and the median of the sample of differences were greater than zero. Because the differences were calculated as the DP well result minus the HAS well result, this indicated that, in these cases, the DP wells produced more conservative results (i.e., higher concentrations) than the HSA wells.

Table 6. Summary of VOA results for statistical tests of differences between analytical results from pairings of 0.5-inch diameter direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
1,1,1-TCA	11	-8.4	30.5	<0.01		0.096	0.12		Accept
1,1,2-TCA	10	3.0	9.0	>0.15	0.328				Accept
1,4-DCB	31	-1.2	32.6	<0.01		<0.01		0.221	Accept
benzene	29	5.6	289.7	<0.01		<0.01		0.050	Reject
cis-1,2-DCE	27	-1.1	83.1	<0.01		>0.15	0.023		Reject
ethylbenzene	31	12.1	31.0	<0.01		<0.01		0.004	Reject
MTBE	12	1.7	54.5	<0.01		<0.01		0.784	Accept
PCE	7	1.5	6.3	0.075	0.546				Accept
trans-1,2-DCE	14	-3.2	13.1	<0.01		>0.15	0.783		Accept
TCE	32	-1.2	114.4	<0.01		0.025		0.978	Accept
toluene	23	-1.0	9.4	<0.01		0.045		0.595	Accept
vinyl chloride	19	-1.5	23.5	<0.01		0.048		0.952	Accept
m,p-xylene	28	13.1	178.4	<0.01		<0.01		0.005	Reject
o-xylene	29	-3.1	64.1	<0.01		<0.01		0.545	Accept

Table 7. Summary of VOA results for statistical tests of differences between analytical results from pairings of 0.75-inch diameter direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
1,1,1-TCA	13	2.6	18.4	0.043		>0.15	0.439		Accept
1,1,2-TCA	10	0.5	6.9	>0.15	0.816				Accept
1,4-DCB	26	4.5	31.7	<0.01		0.096	0.883		Accept
benzene	28	92.9	236.0	<0.01		<0.01		0.086	Accept
cis-1,2-DCE	22	29.1	89.4	<0.01		>0.15	0.97		Accept
ethylbenzene	28	10.9	39.0	<0.01		0.014		0.393	Accept
MTBE	26	14.1	61.0	0.042		<0.01		0.416	Accept
PCE	4	1.9	14.1	0.088	0.808				Accept
trans-1,2-DCE	10	0.4	9.3	0.013		0.069	0.733		Accept
TCE	33	42.9	172.2	<0.01		>0.15	0.274		Accept
toluene	24	23.6	49.4	<0.01		<0.01		0.074	Accept
vinyl chloride	18	10.3	19.9	<0.01		>0.15	0.099		Accept
m,p-xylene	25	42.1	121.2	<0.01		0.061	0.007		Reject

Table 8. Summary of VOA results for statistical tests of differences between analytical results from pairings of 1.5-inch diameter direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
1,1,1-TCA	14	9.7		30.3	0.018		<0.01		Reject
1,1,2-TCA	12	1.2		6.6	>0.15	0.556			Accept
1,4-DCB	30	39.2		90.9	<0.01		0.103	0.003	Reject
benzene	28	67.8		249.3	<0.01		<0.01		Reject
cis-1,2-DCE	21	-2.1		62.7	<0.01		>0.15	0.496	Accept
ethylbenzene	28	47.2		98.3	<0.01		<0.01		Reject
MTBE	13	45.8		89.6	<0.01		>0.15	0.087	Accept
PCE	8	2.6		4.4	>0.15	0.129			Accept
trans-1,2-DCE	13	-5.6		12.0	<0.01		>0.15	0.489	Accept
TCE	34	73.0		232.1	<0.01		>0.15	0.007	Reject
toluene	26	48.6		119.8	<0.01		<0.01		Reject
vinyl chloride	19	-2.9		9.9	>0.15	0.218			Accept
m,p-xylene	29	113.6		261.9	<0.01		0.018	-	Reject
o-xylene	30	80.4		193.3	<0.01		0.042		Reject

Table 9. Summary of VOA results for statistical tests of differences between analytical results from pairings of 2-inch diameter direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
1,1,1-TCA	26	33.7	446.2	<0.01		0.045		0.800	Accept
1,1,2-TCA	17	32.2	165.8	<0.01		0.087	0.918		Accept
1,4-DCB	42	7.1	34.1	<0.01		0.064	0.525		Accept
benzene	38	3.6	32.8	<0.01		>0.15	0.603		Accept
cis-1,2-DCE	44	1913.5	4935.0	<0.01		<0.01		0.354	Accept
ethylbenzene	28	3.5	67.3	<0.01		<0.01		0.241	Accept
MTBE	9	-5.5	10.8	>0.15	0.166				Accept
PCE	30	180.5	719.0	<0.01		0.037		0.821	Accept
trans-1,2-DCE	22	14.2	55.2	<0.01		>0.15	0.392		Accept
TCE	47	191.7	1068.4	<0.01		<0.01		0.691	Accept
toluene	27	122.7	311.6	<0.01		0.142	0.048		Reject
vinyl chloride	39	83.5	301.0	<0.01		0.048		0.818	Accept
m,p-xylene	35	7.3	114.4	<0.01		0.141	0.765		Accept
o-xylene	35	12.3	35.8	<0.01		>0.15	0.036		Reject

Table 10. Summary of VOA results for statistical tests of differences between MTBE results from pairings of direct push wells with drilled (HSA) wells (well types and diameters noted below).

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclusion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
MTBE[1]	27	-6.9	63.8	<0.01		>0.15	0.599		Accept
MTBE[2]	33	8.3	56.2	<0.01		0.041		0.068	Accept
MTBE[3]	12	18.0	75.6	0.032		>0.15	0.468		Accept

[1]Pack Type: ASTM Prepack, Diameter: 2"
[2]Pack Type: ASTM Prepack, Diameter: 0.75"
[3]Pack Type: none, Diameter: 0.75"

The VOC hypothesis testing results for all combinations of DP well pack type and diameter are summarized in Table 11. Interesting to note is that in all cases except the non-ASTM prepacked 0.5-inch wells, where the hypothesis tests showed disagreement between the wells, the DP wells indicated higher concentrations of VOCs on average than the HSA wells. This finding would imply that, with few exceptions, the DP wells produce more conservative contaminant monitoring results with regard to the VOCs tested. In general, the 2" non-packed DP wells and 0.75" non-ASTM prepacked DP wells agreed best with the HSA wells, whereas the 1.5" non-packed wells disagreed most often but were most conservative, and the pre-packed 0.5" wells were least conservative overall. For MTBE, all DP well types were found to agree with HSA wells, but this was the only parameter available for evaluation of the ASTM pre-packed wells and the 0.75' non-packed wells.

Table 11. Summary of hypothesis testing results, indicating where DP well concentrations were found to be equal to (=), greater than (>), and less than (<) HSA concentration.

Pack Type	ASTM Prepack		non-ASTM Prepack		none		
Diameter	0.75"	2"	0.5"	0.75"	0.75"	1.5"	2"
1,1,1-TCA	n/a	n/a	=	=	n/a	>	=
1,1,2-TCA	n/a	n/a	=	=	n/a	=	=
1,4-DCB	n/a	n/a	=	=	n/a	>	=
benzene	n/a	n/a	>	=	n/a	>	=
cis-1,2-DCE	n/a	n/a	<	=	n/a	=	=
ethylbenzene	n/a	n/a	>	=	n/a	>	=
MTBE	=	=	=	=	=	=	=
PCE	n/a	n/a	=	=	n/a	=	=
trans-1,2-DCE	n/a	n/a	=	=	n/a	=	=
TCE	n/a	n/a	=	=	n/a	>	=
toluene	n/a	n/a	=	=	n/a	>	>
vinyl chloride	n/a	n/a	=	=	n/a	=	=
m,p-xylene	n/a	n/a	>	n/a	n/a	>	=
o-xylene	n/a	n/a	=	>	n/a	>	>

The power of the hypothesis tests of VOC data for all DP well pack types and diameters is summarized in Table 12. Tests in which the power met or exceeded the goal of 80%

are indicated with entries in **bold** typeface. One reason why the tests of sufficient power number very few is that the study plan as conceived was to group similar DP wells for hypothesis testing of DP versus HSA wells on a gross basis (for instance, 2" and 1.5" diameter with no pack, or all 0.75" wells regardless of pack type), but the objective was changed mid-project to one of evaluating each combination of DP pack type and diameter individually. Given the new objective, it is recommended that considerable more sampling rounds be undertaken to improve the power it the hypothesis tests.

Table 12. Power of hypothesis tests based on equivalent power of t-test, assuming normal distribution of differences or differences of logs.

Pack Type	**ASTM Prepack**		**non-ASTM Prepack**		**none**		
Diameter	**0.75"**	**2"**	**0.5"**	**0.75"**	**0.75"**	**1.5"**	**2"**
1,1,1-TCA	n/a	n/a	0.34	0.11	n/a	0.20	0.07
1,1,2-TCA	n/a	n/a	0.15	0.06	n/a	0.09	0.05
1,4-DCB	n/a	n/a	0.05	0.05	n/a	**0.88**	0.10
benzene	n/a	n/a	0.05	0.51	n/a	0.28	0.08
cis-1,2-DCE	n/a	n/a	0.64	0.05	n/a	0.10	0.71
ethylbenzene	n/a	n/a	0.55	0.30	n/a	0.69	0.06
m,p-xylene	n/a	n/a	0.07	**0.80**	n/a	0.62	0.06
MTBE	0.13	0.08	0.05	0.21	0.11	0.40	0.27
o-xylene	n/a	n/a	0.06	0.23	n/a	0.60	0.57
PCE	n/a	n/a	0.08	0.05	n/a	0.32	0.26
TCE	n/a	n/a	0.05	0.19	n/a	**0.80**	0.23
toluene	n/a	n/a	0.08	0.61	n/a	0.51	0.52
trans-1,2-DCE	n/a	n/a	0.06	0.06	n/a	0.10	0.13
vinyl chloride	n/a	n/a	0.06	0.38	n/a	0.23	0.39

5.3.4. Inorganics Analytical Data

Analyses for inorganic species and other water quality parameters were conducted on samples from four rounds of sampling at all sites. Table 13 summarizes the laboratory analyses that were performed.

Table 13. Summary of analyses conducted for inorganic analytes and other water quality parameters on four sampling rounds at all sites.

Analytical Method	Analyte/Parameter (units)
EPA 130.2 (modified)	Total Hardness (mg/L as $CaCO_3$)
EPA 160.1	Total Dissolved Solids (mg/L)
EPA 300.0	Chloride (mg/L)
EPA 300.0	Fluoride (mg/L)
EPA 300.0	Sulfate (mg/L)
EPA 310.1	Alkalinity to pH 4.5
EPA 310.1	Alkalinity to pH 8.3
EPA 353.2	Nitrate Nitrogen (mg/L)
SM-18 2320B	Bicarbonate (mg/L as $CaCO_3$)
SM-18 2320B	Carbonate (mg/L as $CaCO_3$)
SM-18 2320B	Hydroxide (mg/L as $CaCO_3$)
SW-846 6010B	Boron (mg/L)
SW-846 6010B	Calcium (mg/L)
SW-846 6010B	Iron (mg/L)
SW-846 6010B	Magnesium (mg/L)
SW-846 6010B	Manganese (mg/L)
SW-846 6010B	Potassium (mg/L)
SW-846 6010B	Sodium (mg/L)

The results of the inorganics analyses were analyzed by the same statistical procedures as the VOA results, and are summarized in Table 14 through Table 20.

Table 14. Summary of statistical tests of differences between inorganic analytical results from pairings of 2-inch diameter ASTM Prepack direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclusion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
Alkalinity	17	-7.588	14.522	>0.15	0.047				Reject
Bicarbonate	17	-7.588	14.522	>0.15	0.047				Reject
Boron	17	-0.044	0.151	>0.15	0.250				Accept
Calcium	17	-4.471	24.495	>0.15	0.463				Accept
Chloride	17	-1.706	6.687	>0.15	0.309				Accept
Fluoride	12	-0.037	0.058	>0.15	0.051				Accept
Iron	11	0.050	0.214	0.043		>0.15	0.770		Accept
Magnesium	17	-2.412	10.926	>0.15	0.376				Accept
Manganese	17	0.069	0.241	>0.15	0.253				Accept
Potassium	17	-0.537	0.960	<0.01		>0.15	0.041		Reject
Sodium	17	-4.118	15.660	>0.15	0.294				Accept
Sulfate	17	-22.353	117.289	>0.15	0.443				Accept
TDS	17	-44.706	103.870	>0.15	0.095				Accept
Total Hardness	17	-21.765	98.313	>0.15	0.375				Accept

Table 15. Summary of statistical tests of differences between inorganic analytical results from pairings of 0.75-inch diameter ASTM Prepack direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P		P	P	P	H_0: μ=0
Alkalinity	19	-3.474	11.102	>0.15	0.189				Accept
Bicarbonate	19	-3.474	11.102	>0.15	0.189				Accept
Boron	19	0.016	0.144	>0.15	0.628				Accept
Calcium	19	1.526	19.415	>0.15	0.736				Accept
Chloride	19	-0.947	4.859	>0.15	0.407				Accept
Fluoride	13	-0.060	0.086	>0.15	0.027				Reject
Iron	14	0.066	0.264	0.089	0.367				Accept
Magnesium	19	0.895	8.279	>0.15	0.643				Accept
Manganese	19	0.006	0.111	>0.15	0.823				Accept
Nitrate	3	0.477	0.393	>0.15	0.170				Accept
Potassium	19	-0.367	0.631	<0.01		>0.15	0.011		Reject
Sodium	19	-1.368	9.668	>0.15	0.545				Accept
Sulfate	19	-32.632	105.769	>0.15	0.195				Accept
TDS	19	-27.895	96.643	>0.15	0.224				Accept
Total Hardness	19	-10.000	86.987	>0.15	0.622				Accept

Table 16. Summary of statistical tests of differences between inorganic analytical results from pairings of 0.75-inch diameter non-ASTM Prepack direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
Alkalinity	32	-1.200	10.750	>0.15	0.532				Accept
Bicarbonate	32	-1.200	10.750	>0.15	0.532				Accept
Boron	32	-0.006	0.273	<0.01		0.071	0.983		Accept
Calcium	32	-1.833	11.267	<0.01		<0.01		0.926	Accept
Chloride	32	0.563	5.883	<0.01		0.084	0.370		Accept
Fluoride	9	-0.042	0.068	>0.15	0.099				Accept
Iron	29	0.156	0.341	>0.15	0.020				Reject
Magnesium	32	-0.799	5.062	<0.01		>0.15	0.297		Accept
Potassium	32	-0.039	1.423	0.029		>0.15	0.367		Accept
Sodium	32	0.597	11.190	<0.01		>0.15	0.233		Accept
Sulfate	32	-8.022	71.694	<0.01		<0.01		0.545	Accept
TDS	32	-2.469	45.601	<0.01		0.065	0.319		Accept
Total Hardness	32	-12.681	55.605	<0.01		>0.15	0.433		Accept

Table 17. Summary of statistical tests of differences between inorganic analytical results from pairings of 0.5-inch diameter non-ASTM Prepack direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
Alkalinity	24	-3.657	13.828	<0.01		<0.01		0.166	Accept
Bicarbonate	24	-3.657	13.828	<0.01		<0.01		0.166	Accept
Boron	24	-0.055	0.308	<0.01		>0.15	0.896		Accept
Calcium	23	-1.801	4.842	<0.01		<0.01		0.075	Accept
Chloride	24	-0.242	1.174	>0.15	0.324				Accept
Fluoride	3	-0.080	0.131	>0.15	0.400				Accept
Iron	21	0.171	0.608	0.039		<0.01		0.095	Accept
Magnesium	24	-0.191	0.439	<0.01		>0.15	0.446		Accept
Manganese	23	0.283	0.940	<0.01		<0.01		0.001	Reject
Potassium	24	-0.145	3.101	<0.01		>0.15	0.505		Accept
Sodium	24	-0.074	1.004	0.029		<0.01		0.853	Accept
Sulfate	24	-2.446	4.686	<0.01		0.079	0.053		Accept
TDS	24	-2.333	20.175	>0.15	0.576				Accept
Total Hardness	24	-5.217	17.523	0.037		0.12	0.222		Accept

Table 18. Summary of statistical tests of differences between inorganic analytical results from pairings of 2-inch diameter (no pack) direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclu-sion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
Alkalinity	29	12.858	44.943	<0.01		<0.01		0.462	Accept
Bicarbonate	24	13.970	44.353	<0.01		<0.01		0.449	Accept
Boron	12	0.004	0.019	>0.15	0.499				Accept
Calcium	29	7.096	23.501	<0.01		<0.01		0.073	Accept
Carbonate	7	5.430	45.018	<0.01		>0.15	0.184		Accept
Chloride	29	12.860	22.961	<0.01		<0.01		0.000	Reject
Fluoride	6	0.147	0.106	<0.01		<0.01		0.059	Accept
Iron	18	-0.587	8.665	<0.01		<0.01		0.433	Accept
Manganese	28	0.492	1.534	<0.01		<0.01		0.017	Reject
Potassium	29	-0.149	2.277	<0.01		<0.01		0.345	Accept
Sodium	29	4.505	7.712	<0.01		<0.01		0.000	Reject
Sulfate	29	4.441	9.015	>0.15	0.013				Reject
TDS	28	37.027	84.821	0.012		<0.01	0.017		Reject
Total Hardness	29	30.847	85.802	<0.01		<0.01		0.019	Reject

Table 19. Summary of statistical tests of differences between inorganic analytical results from pairings of 1.5-inch diameter (no pack) direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclusion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
Alkalinity	24	1.288	21.492	>0.15	0.772				Accept
Bicarbonate	24	-3.657	13.828	<0.01		<0.01		0.166	Accept
Boron	24	0.003	0.429	<0.01		0.129	0.249		Accept
Calcium	23	-0.872	7.424	<0.01		>0.15	0.753		Accept
Chloride	24	0.167	3.143	<0.01		>0.15	0.481		Accept
Fluoride	3	-0.113	0.101	0.106	0.192				Accept
Iron	21	-0.117	0.594	<0.01		0.04		0.979	Accept
Magnesium	24	-0.189	0.892	<0.01		<0.01		0.553	Accept
Manganese	24	-0.005	0.111	<0.01		>0.15	0.010		Reject
Potassium	24	-0.120	3.725	<0.01		>0.15	0.991		Accept
Sodium	21	0.113	1.984	>0.15	0.797				Accept
Sulfate	24	-4.783	7.296	>0.15	0.004				Reject
TDS	24	-3.250	32.177	>0.15	0.625				Accept
Total Hardness	24	-4.813	24.767	0.03		0.046		0.864	Accept

Table 20. Summary of statistical tests of differences between inorganic analytical results from pairings of 0.75-inch diameter (no pack) direct push wells with drilled (HSA) wells.

Analyte	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S Normality Test (logs)	Paired t Test (logs)	Wilcoxon Matched Pairs Test	Conclusion
		Mean	St. Dev.						
Name	N	μ	σ	P	P	P	P	P	H_0: μ=0
Alkalinity	7	-2.286	9.429	>0.15	0.545				Accept
Bicarbonate	7	-0.016	0.102	>0.15	0.696				Accept
Boron	7	0.016	0.101	>0.15	0.696				Accept
Calcium	7	0.286	11.011	>0.15	0.947				Accept
Chloride	7	-1.286	5.964	>0.15	0.589				Accept
Fluoride	5	-0.026	0.083	>0.15	0.522				Accept
Iron	6	-0.313	0.153	>0.15	0.637				Accept
Magnesium	7	0.000	5.000	>0.15	1.000				Accept
Manganese	7	0.107	0.162	>0.15	0.131				Accept
Potassium	7	-0.203	0.683	>0.15	0.462				Accept
Sodium	7	-2.286	9.690	0.133	0.556				Accept
Sulfate	7	-17.143	87.885	>0.15	0.624				Accept
TDS	7	24.286	66.548	>0.015	0.372				Accept
Total Hardness	7	-1.429	95.469	>0.15	0.970				Accept

The inorganics hypothesis testing results for all combinations of DP well pack type and diameter are summarized in Table 21. Interesting to note is that for the non-packed DP wells and the non-ASTM packed DP wells, the results for the DP wells are consistently greater than the results for the HSA wells, but for the ASTM prepacked DP wells, the signs of the differences are mixed. Overall, the 2" DP wells with ASTM prepack

disagreed most often with the HSA wells, while the unpacked 0.75" wells agreed in every case.

Table 21. Summary of hypothesis testing results, indicating where DP well concentrations were found to be equal to (=), greater than (>), and less than (<) HSA concentration.

Pack Type	ASTM Prepack		non-ASTM Prepack		none		
Diameter	0.75"	2"	0.5"	0.75"	0.75"	1.5"	2"
Alkalinity	=	<	=	=	=	=	=
Bicarbonate	=	<	=	=	=	=	=
Boron	=	>	=	=	=	=	=
Calcium	=	>	=	=	=	=	=
Carbonate	=	n/a	n/a	n/a	=	n/a	=
Chloride	=	>	=	=	=	=	>
Fluoride	<	>	=	=	=	=	=
Iron	=	>	=	>	=	=	=
Magnesium	=	>	=	=	=	=	n/a
Manganese	=	>	>	n/a	=	-	>
Potassium	<	<	=	=	=	=	=
Sodium	=	>	=	=	=	=	>
Sulfate	=	>	=	=	=	<	>
TDS	=	>	=	=	=	=	>
Total Hardness	=	>	=	=	=	=	>

The power of the hypothesis tests of inorganics data for all DP well pack types and diameters is summarized in Table 22. Tests in which the power met or exceeded the goal of 80% are indicated with entries in **bold** typeface. Generally, the power of these tests was greater than for the VOC tests of hypothesis. This is likely due to the linear distribution of inorganics data relative to VOCs, which can span several orders of magnitude. This fact is also reflected in the greater number of inorganics data sets that exhibited normal distributions without the need to log-transform the data (see Tables above). One reason why the tests of sufficient power number very few is that the study plan as conceived was to group similar DP wells for hypothesis testing of DP versus HSA wells on a gross basis (for instance, 2" and 1.5" diameter with no pack, or all 0.75" wells regardless of pack type), but the objective was changed mid-project to one of evaluating each combination of DP pack type and diameter individually. Given the new objective, it is recommended that considerable more sampling rounds be undertaken to improve the power it the hypothesis tests.

Table 22. Power of hypothesis tests based on equivalent power of t-test, assuming normal distribution of differences or differences of logs.

Pack Type	ASTM Prepack		non-ASTM Prepack		none		
Diameter	**0.75"**	**2"**	**0.5"**	**0.75"**	**0.75"**	**1.5"**	**2"**
Alkalinity	0.25	0.53	0.24	0.09	0.08	0.06	0.32
Bicarbonate	0.25	0.53	0.24	0.09	0.06	0.06	0.32
Boron	0.08	0.20	0.05	0.05	0.08	0.21	0.10
Calcium	0.06	0.11	0.40	0.14	0.05	0.06	0.35
Carbonate	n/a	n/a	n/a	n/a	n/a	n/a	0.25
Chloride	0.13	0.17	0.16	0.14	0.08	0.11	**0.83**
Fluoride	0.64	0.52	0.10	0.38	0.09	0.21	0.77
Iron	0.14	0.06	0.23	0.66	**0.98**	0.14	0.06
Magnesium	0.07	0.14	0.12	0.18	0.05	0.17	n/a
Manganese	0.06	0.20	0.28	n/a	0.31	0.77	0.37
Nitrate	0.23	n/a	n/a	n/a	n/a	n/a	n/a
Potassium	0.77	0.55	0.10	0.14	0.10	0.05	0.06
Sodium	0.09	0.18	0.06	0.22	0.08	0.06	0.09
Sulfate	0.25	0.11	0.50	0.09	0.07	**0.87**	0.73
TDS	0.22	0.39	0.08	0.06	0.13	0.08	0.46
Total Hardness	0.08	0.14	0.23	0.24	0.05	0.15	0.46

5.3.5. Purge Parameters

In addition to the VOCs and inorganics, water quality parameters that the low-stress sampling protocol requires to be monitored during purging were subjected to statistical tests of hypothesis. For these tests, the final value of the purge parameter recorded on the sampling logs (i.e., the stabilized reading) was used. The results are summarized in Table 23 through Table 26. Observations to note include:

- The proportion of purge parameters for which there is no statistically significant difference between DP and HSA wells is much less than the proportion of VOCs and inorganics for which there is no statistically significant difference.
- Purge volumes were consistently in agreement between DP wells and HSA wells, regardless of the differences in well diameter. This is surprising given the differences in purge rates that would have resulted from adherence to the minimum drawdown constraints of the low-stress sampling procedure over the wide range of screen areas present.
- The number of valid data pairs varied considerably within a given sample (e.g., DP well size), despite there being no possibility of non-detects in this type of measurements. These were the result of missing data and equipment failures.
- Except for the well pairs that involve 0.75" DP wells, turbidity was comparable between DP and HSA wells. This occurred despite the absence of a non-native sand pack on most of the 2" DP wells (22 of 26) and all of the 1.5" and 1" DP wells. Turbidity was much higher in the narrow 0.75" DP wells than in the 2" HSA wells.

A relatively high degree of variability in the purge parameter data was expected, since significantly less stringent procedures were applied to the calibration and maintenance of purge monitoring equipment than to laboratory analytical procedures. Nevertheless, the added intra-well variation should widen the confidence limits of the test, rendering the null hypothesis accordingly easier to accept. Other possible explanations for the inconsistent findings with regard to purge parameters include the possibilities that:

- The final value recorded may have not in some cases represented a stable reading.
- Differences in residence time of groundwater in the sampling pump tubing influenced the temperatures observed which may have had an effect on other measurements. (Where temperatures disagreed, ORP and D.O. also tended to disagree). Separation and analysis of the data by season may help assess the likelihood of such a phenomenon.

Table 23. Summary of results for statistical tests of differences between final purge monitoring results from pairings of 2-inch diameter direct push wells with drilled (HSA) wells.

Parameter	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S log-Normality Test	Paired t Test	Wilcoxon Matched Pairs Test	Result
		Mean	Median						
Name	N	μ		P	P	P	P	P	H_0: μ=0
pH	133	-0.16	-0.01	<0.010		<0.010		0.002	Reject
ORP	55	61.1	18	<0.010		<0.010		0.000	Reject
Temperature	133	-0.1	0.1	<0.010		<0.010		0.046	Reject
Specific Cond.	129	-0.14	-0.02	<0.010		<0.010		0.003	Reject
D.O.	112	0.35	0.06	<0.010		<0.010		0.000	Reject
Turbidity	118	25.2	1.2	<0.010		<0.010		0.782	Accept
Purge Volume	19	1.41	3	<0.010		<0.010		0.251	Accept

Table 24. Summary of results for statistical tests of differences between final purge monitoring results from pairings of 1.5-inch diameter direct push wells with drilled (HSA) wells.

Parameter	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S log-Normality Test	Paired t Test	Wilcoxon Matched Pairs Test	Result
		Mean	Median						
Name	N	µ		P	P	P	P	P	$H_0: \mu=0$
pH	44	11.41	0.005	<0.010		<0.010		0.578	Accept
ORP	44	-19.9	-14.25	<0.010		<0.010		0.003	Reject
Temperature	43	0.00	0.00	<0.010		<0.010		0.786	Accept
Specific Cond.	44	-0.02	-0.01	<0.010		0.029		0.127	Accept
D.O.	43	-0.07	-0.04	<0.010		0.047		0.395	Accept
Turbidity	43	11.5	0.6	<0.010		<0.010		0.244	Accept
Purge Volume	21	0.17	0	>0.150	0.560				Accept

Table 25. Summary of results for statistical tests of differences between final purge monitoring results from pairings of 1-inch diameter direct push wells with drilled (HSA) wells.

Parameter	Pairs in Test	Difference (DP-HSA)		K-S Normality Test	Paired t Test	K-S log-Normality Test	Paired t Test	Wilcoxon Matched Pairs Test	Result
		Mean	Median						
Name	N	µ		P	P	P	P	P	$H_0: \mu=0$
pH	234	0.04	0.02	<0.010		<0.010		0.000	Reject
ORP	43	-14.1	-0.4	<0.010		>0.15	0.021		Reject
Temperature	234	0.37	0.05	<0.010		<0.010		0.000	Reject
Specific Cond.	234	-0.02	-0.01	<0.010		<0.010		0.000	Reject
D.O.	150	-0.08	-0.08	<0.010		<0.010		0.000	Reject
Turbidity	234	1.36	0	<0.010		<0.010		0.605	Accept
Purge Volume	20	-0.07	0	>0.150	0.846				Accept

Table 26. Summary of results for statistical tests of differences between final purge monitoring results from pairings of 0.75-inch diameter direct push wells with drilled (HSA) wells.

Parameter	Pairs in Test	Difference (DP-HSA) (ppb)		K-S Normality Test	Paired t Test	K-S log-Normality Test	Paired t Test	Wilcoxon Matched Pairs Test	Result
		Mean	Median						
Name	N	µ		P	P	P	P	P	$H_0: \mu=0$
pH	42	-0.062	-0.01	<0.010		<0.010		0.231	Accept
ORP	42	-6.9	2.6	<0.010		>0.150	0.599		Accept
Temperature	42	-0.10	-0.07	<0.010		0.024		0.291	Accept
Specific Cond.	42	-0.01	-0.01	<0.010		0.096	0.022		Reject
D.O.	41	-0.15	-0.08	<0.010		0.052	0.229		Accept
Turbidity	41	15.67	5.6	<0.010		<0.010		0.000	Reject
Purge Volume	18	0.14	0	>0.150	0.707				Accept

5.3.6. ANOVA Analysis

Analysis of variance (ANOVA) studies the effect of nominal independent variables on a continuous dependent variable. Nominal variables can take on a limited number of values (e.g., well type, nominal diameter). Continuous variables are presumably dependent data that can take on any value. Continuous variables would include chemical concentrations, purge times, etc. The ANOVA produces the *mean square* statistic, which indicates the F-value and associated P-value for each combination of a nominal variable with the continuous variable analyzed. The P-value quantifies how much of the variability in the continuous variable is correlated with variability in the nominal variable (i.e., how much variation in the chemical constituent concentration can be explained by a difference in the value of the discrete variable). ANOVA was performed on data from wells at both the Tyndall and Port Hueneme sites. Nominal variables consisted of well diameter, installation technique, and the presence or absence of a well pack (i.e., non-native material filling an annular space around the well screen).

A select group of well clusters at both Port Hueneme and Tyndall were evaluated using ANOVA techniques. At Tyndall, benzene, ethylbenzene, o-xylene, PDCB and TCE concentrations were evaluated for the effects of well type (e.g., DP or HSA) and well diameter as independent variables. At Port Hueneme, MTBE, TDS, and hardness were analyzed, again, to determine the influence of well type and diameter. After testing the data (or log data) for normality, the appropriate One-way Repeated Measures ANOVA test (RM-ANOVA) or the Friedman One-way RM-ANOVA on Ranks test was performed. At Port Hueneme, the two sites were treated separately because of the difference in the number of wells in each of the clusters (3 vs. 5). Statistical analyses were conducted only on analytes where there was sufficient data for comparison.

At Tyndall Air Force Base, concentrations of TCE, benzene, and o-xylene were significantly higher in the 1.5-inch DP wells (with no-pre-pack) than in the 2-inch HSA wells (with conventional sand pack). Also of interest, concentrations of TCE and o-xylene were also significantly higher in the ½-inch DP wells (with pre-pack) than the 2-inch HSA wells, and concentrations of ethylbenzene were significantly higher in the 1/2-inch DP wells than the 2-inch DP wells. Well construction details include:

- 2-inch HSA well with conventional sand pack,
- 1.5-inch DP well, quasi-static installation, no pre-pack
- 1-inch DP well, hammer installation, with pre-pack,
- 0.5-inch DP well, hammer installation, with pre-pack
- 10'screens (except for one cluster of 15' screens, and two clusters of 25') screens

Table 27. Comparison of Direct Push -vs- Conventional wells at Tyndall AFB.

Analyte	*Sig. Difference ? 95% Confidence*	*Type of test (p-Value)*	*Differences by Tukey Test (p-Value)*
Benzene	Yes	One-way RM-ANOVA on log data** (0.012)	2" HSA and 1.5" DP* (0.007)
Ethyl-benzene	Yes	One-way Friedman RM-ANOVA on Ranks (0.0260)	2" HSA and 0.5" DP* (<0.050)
o-xylene	Yes	One-way RM-ANOVA on log data (0.005)	2" HSA and 1.5" DP* (0.007) 1.5" DP* and 0.5"DP (0.015)
PDCB	No	One-way RM-ANOVA on log data	
TCE	Yes	One-way RM-ANOVA on log data (0.001)	2" HSA and 1.5" DP* (0.036) 1.5" DP* and .5" DP (<0.001)#

* **Wells with larger values**

** **Data not normally distributed but test is more powerful than one-way Friedman ANOVA on ranks.**

\# **Does not give actual probability.**

There were no significant differences between any of the well types for Total Hardness or Total Dissolved Solids at either site A or B at Port Hueneme. At site A, concentrations of MTBE were significantly higher in the ¾-inch DP wells (ASTM designed) than in the 2-inch HSA wells (ASTM designed). There was no significant difference between the concentrations of MTBE in the 2-inch ASTM designed HSA or DP wells. At site B, the only significant difference in MTBE concentrations in any of the five well types were between the 2-inch HSA and the 2-inch DP wells, and in this instance concentrations were higher in the HSA well. Well types at site A include:

- 2-inch HSA, ASTM design, 2' and 5' screens
- 2-inch DP, ASTM design pre-pack, 2' and 5' screens
- 0.75-inch DP, ASTM design pre-pack, 2' and 5' screens

Table 28. Comparison of Direct Push -vs- Conventional wells at site A, Port Hueneme.

Analyte	Sig. Difference ? 95% Confidence	Type of test (p-Value)	Differences by Tukey Test (p-Value)
MTBE	Yes	One-way RM-ANOVA on data (0.005)	0.75"-DP* and 2"-HAS (0.004)
TDS	No	One-way RM-ANOVA on data	
HARD	No	One-way RM-ANOVA on data	

Well types at Site B include:

- 2-inch HSA well, ASTM design, 2' and 5' screens
- 2-inch DP well, ASTM design pre-pack, 2' and 5' screens
- 0.75-inch DP well, ASTM design pre-pack, 2' and 5' screens'
- 0.75-inch DP well, no pre-pack, 2' and 5' screens
- 0.75-inch DP well, conventional designed pre-pack

Table 29. Comparison of Direct Push -vs- Conventional wells at site B, Port Hueneme.

Analyte	Sig. Difference? 95% Confidence	Type of test (p-Value)	Differences by Tukey Test (p-Value)
MTBE	Yes	One-way RM-ANOVA on log data (0.013)	2"-DP and 2"-HSA* (0.007)
TDS	No	One-way RM-ANOVA on data	
HARD	No	One-way RM-ANOVA on data	

*** Wells with larger values**

In summary, no significant difference was detected at any of the sites for the inorganic parameters such as Total Dissolved Solids and Total Hardness. With only one exception, concentrations of VOCs are either not significantly different in DP wells than in conventional wells or they are significantly higher in the DP wells. This data indicates that DP wells are reliable and conservative in representing contamination at a site.

5.3.7. Slug Test Data

The objective of conducting the slug tests was to identify the influence of different well geometries and installation techniques on the apparent hydraulic conductivity of the formation as measured via slug tests.

A total of 35 individual slug tests were conducted at Port Hueneme within test cell 'B'. One of the clusters, B4, consists of five individual wells of various configurations and was selected for testing based on CPT data analysis, depth to static water table, screen lengths, and well diameters. The CPT data showed uniform material (sand) throughout the depth interval of all of the screened portions of the individual wells. The water table was sufficiently high to insure that the water table would not be depressed below the top of the screened interval during the test. The well construction details were similar to that of most of the wells used in the LTM study.

The slug tests were conducted utilizing a pneumatic method to depress the water table within the well, then quickly releasing the gas pressure and monitoring the hydraulic pressure response by means of down-hole pressure transducer as the water rises to its static level. This is essentially a rising head slug test and the data can be analyzed using standard techniques. The apparatus used to conduct these tests consisted of a pneumatic source (e.g., N_2), a data logger and the pneumatic slug test apparatus. These components are shown in Figure 10 and Figure 11.

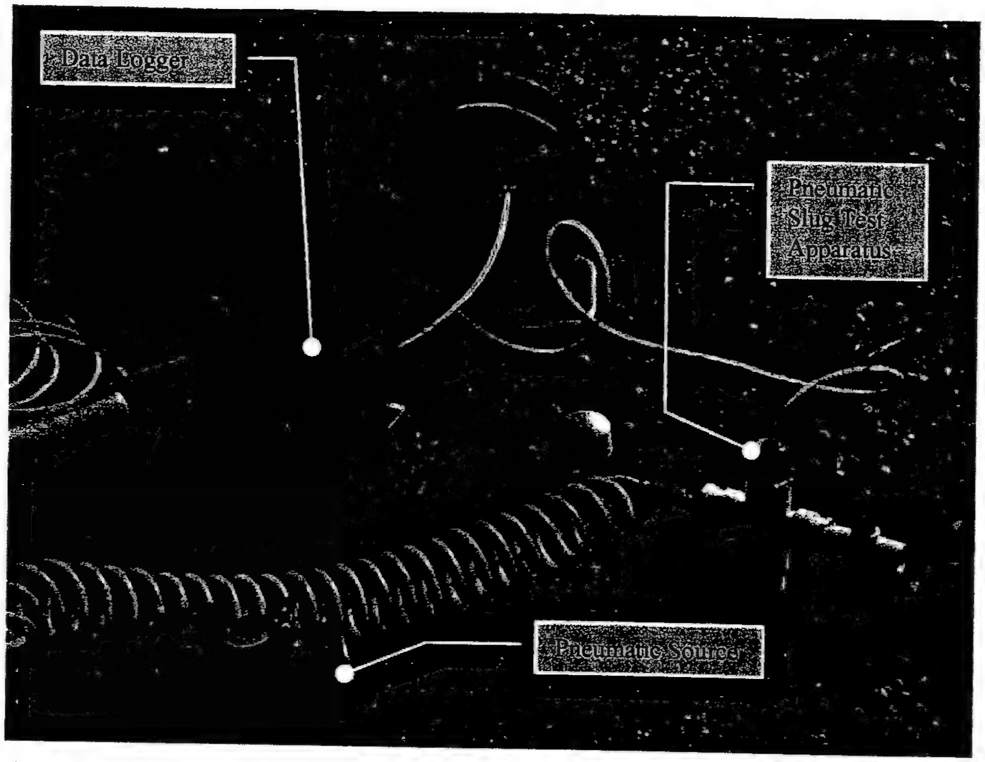

Figure 10. Pneumatic test equipment layout.

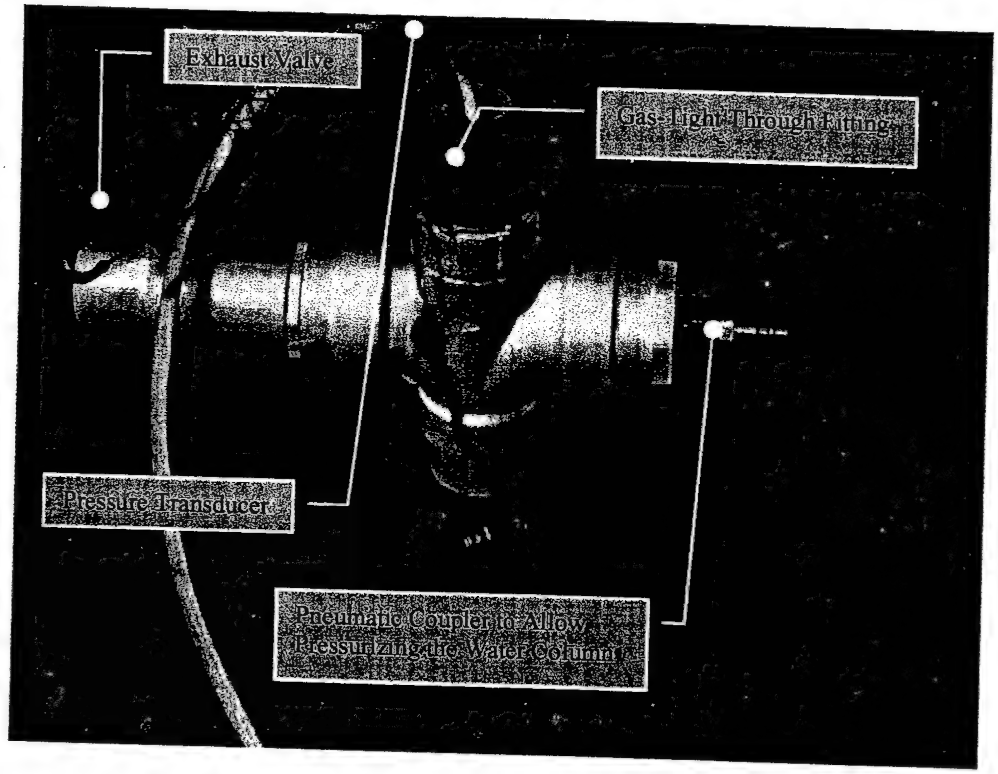

Figure 11. Pneumatic slug test apparatus.

The data were analyzed in accordance with the standard Bouwer-Rice (1976)[2] technique using Waterloo Hydrogeologic's Aquifer Test® software package. The data requirements for the Bouwer-Rice solution are:

- r = piezometer radius.
- R = radius measured from center of well to undisturbed aquifer material.
- R_{cont} = contributing radial distance over which the difference in head, h_0,, is dissipated in the aquifer.
- L = the length of the screen.
- h_t = displacement as f function of time (h_t/h_0 must always be less than zero, i.e. water level must always approach the static water level as time increases).
- h_0 = initial displacement.

Table 30 presents a summary of the input parameters for the wells studied along with the resulting conductivity values. Figure 12 illustrates the mechanics and geometry of a slug test conducted using the Bouwer-Rice solution as implemented in the software. Appendix D contains the time series data and plots.

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[2] Bouwer, H. and R.C. Rice, 1976. A Slug Test Method for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells, Water Resources Research, vol. 12, no. 3, pp. 423-428.

Table 30. Summary of input parameters and conductivity results obtained using the Bouwer-Rice technique.

WELL ID	TEST NAME	ANALYSIS METHOD	CONDUCTIVITY (m/s)	TEST WELL	DISTURBED FORMATION RADIUS (ft)	SCREEN LENGTH (ft)	AQUIFER THICKNESS (ft)	CASING RADIUS (ft)
B4-1	B4-1-1	Bouwer-Rice	8.07E-05	B4-1	0.104	5.0	11.8	0.031
B4-1	B4-1-2	Bouwer-Rice	7.53E-05	B4-1	0.104	5.0	11.8	0.031
B4-1	B4-1-3	Bouwer-Rice	7.30E-05	B4-1	0.104	5.0	11.8	0.031
B4-1	B4-1-4	Bouwer-Rice	7.30E-05	B4-1	0.104	5.0	11.8	0.031
B4-1	B4-1-5	Bouwer-Rice	8.09E-05	B4-1	0.104	5.0	11.8	0.031
B4-1	B4-1-6	Bouwer-Rice	8.97E-05	B4-1	0.104	5.0	11.8	0.031
B4-1	B4-1-7	Bouwer-Rice	1.02E-04	B4-1	0.104	5.0	11.8	0.031
B4-2	B4-2-1	Bouwer-Rice	4.00E-05	B4-2	0.104	5.0	11.8	0.031
B4-2	B4-2-2	Bouwer-Rice	3.54E-05	B4-2	0.104	5.0	11.8	0.031
B4-2	B4-2-3	Bouwer-Rice	3.28E-05	B4-2	0.104	5.0	11.8	0.031
B4-2	B4-2-4	Bouwer-Rice	3.19E-05	B4-2	0.104	5.0	11.8	0.031
B4-2	B4-2-5	Bouwer-Rice	3.14E-05	B4-2	0.104	5.0	11.8	0.031
B4-2	B4-2-6	Bouwer-Rice	3.07E-05	B4-2	0.104	5.0	11.8	0.031
B4-2	B4-2-7	Bouwer-Rice	3.05E-05	B4-2	0.104	5.0	11.8	0.031
B4-3	B4-3-1	Bouwer-Rice	3.11E-05	B4-3	0.104	5.0	11.8	0.031
B4-3	B4-3-2	Bouwer-Rice	2.86E-05	B4-3	0.104	5.0	11.8	0.031
B4-3	B4-3-3	Bouwer-Rice	2.76E-05	B4-3	0.104	5.0	11.8	0.031
B4-3	B4-3-4	Bouwer-Rice	2.75E-05	B4-3	0.104	5.0	11.8	0.031
B4-3	B4-3-5	Bouwer-Rice	2.71E-05	B4-3	0.104	5.0	11.8	0.031
B4-3	B4-3-6	Bouwer-Rice	2.76E-05	B4-3	0.104	5.0	11.8	0.031
B4-3	B4-3-7	Bouwer-Rice	2.84E-05	B4-3	0.104	5.0	11.8	0.031
B4-4	B4-4-1	Bouwer-Rice	2.52E-04	B4-4	0.146	5.0	11.8	0.083
B4-4	B4-4-2	Bouwer-Rice	2.47E-04	B4-4	0.146	5.0	11.8	0.083
B4-4	B4-4-3	Bouwer-Rice	2.50E-04	B4-4	0.146	5.0	11.8	0.083
B4-4	B4-4-4	Bouwer-Rice	2.53E-04	B4-4	0.146	5.0	11.8	0.083
B4-4	B4-4-5	Bouwer-Rice	2.61E-04	B4-4	0.146	5.0	11.8	0.083
B4-4	B4-4-6	Bouwer-Rice	2.54E-04	B4-4	0.146	5.0	11.8	0.083
B4-4	B4-4-7	Bouwer-Rice	2.54E-04	B4-4	0.146	5.0	11.8	0.083
B4-5	B4-5-1	Bouwer-Rice	2.42E-05	B4-5	0.333	5.0	11.8	0.083
B4-5	B4-5-2	Bouwer-Rice	2.42E-05	B4-5	0.333	5.0	11.8	0.083
B4-5	B4-5-3	Bouwer-Rice	2.41E-05	B4-5	0.333	5.0	11.8	0.083
B4-5	B4-5-4	Bouwer-Rice	2.40E-05	B4-5	0.333	5.0	11.8	0.083
B4-5	B4-5-5	Bouwer-Rice	2.41E-05	B4-5	0.333	5.0	11.8	0.083
B4-5	B4-5-6	Bouwer-Rice	1.42E-04	B4-5	0.333	5.0	11.8	0.083
B4-5	B4-5-7	Bouwer-Rice	1.44E-04	B4-5	0.333	5.0	11.8	0.083

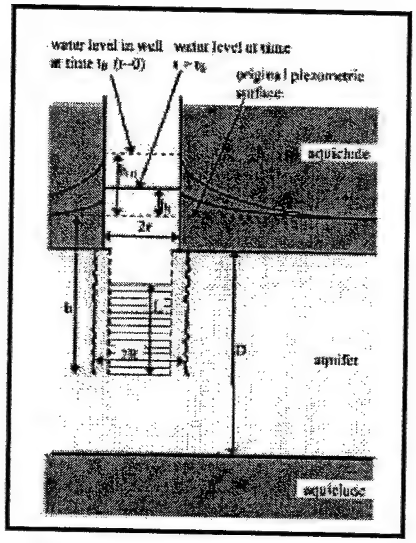

Figure 12. Mechanics and Geometry of a slug test conducted using the Bouwer-Rice solution.

Descriptive statistics from the slug test data are shown in Table 31 below. As indicated by the coefficient of variation (defined as the ratio of the standard deviation divided by the mean) for the test series on each well, the HSA well produced the least consistent slug test results, followed by the 0.75-inch diameter DP well with no sand pack. A closer look at the hydraulic conductivity data for well ID B4-5 in Table 30 shows that the first five tests were consistent then increased by nearly an order of magnitude for the last two tests, matching more closely with the average value of the 2-inch diameter DP well. This might suggest that the well was clogged and was effectively 'developed' during the course of the test series.

The remaining DP wells produced slug test results that were highly consistent within a well, but varied greatly among wells. Also, an examination of the descriptive statistics, considering only the 0.75-inch DP wells, indicates that the presence of a sand pack restricts flow by a factor of approximately 3:1. The 0.75-inch DP well with no sand pack produced higher conductivity estimates than the 0.75-inch DP wells with sand pack, indicating that the absence of a sand pack improves the hydraulic performance of wells in this particular formation.

The findings at port Hueneme agrees with recent literature (Butler, *et. al.,* 2002) that concludes that small diameter wells appear to constrict flow reducing the apparent hydraulic conductivity of aquifer at conductivities above 70 m /day. The data from the current study indicates that this phenomena may occur at conductivities down to approximately 22 m/day.

Table 31. Descriptive statistics of multiple slug tests conducted on each well in a cluster at Port Hueneme

Well ID	Install Method	Diameter (in)	Sand Pack Grain Size (in)	Slot Size (in)	Number of Slug Tests, N	Hydraulic Conductivity, k (10^{-5} m/s)		
						Mean	Median	Coeff. of Variation
B4-1	DP	0.75	no pack	.010	7	8.21	8.07	0.13
B4-2	DP	0.75	.010-.020	.020	7	3.32	3.19	0.10
B4-3	DP	0.75	.020-.040	.010	7	2.83	2.76	0.05
B4-4	DP	2	.010-.020	.020	7	25.3	25.3	0.02
B4-5	HSA	2	.010-.020	.020	7	5.81	2.42	1.0

6. Cost Assessment

6.1 Cost Performance

Table 32 presents typical costs for the installation, and development of direct push style wells. These costs, presented on a per-day basis, are based on typical installations using a percussion style rig and a CPT rig. They assume the installation of 2-inch diameter direct push wells. Sampling costs are based on experience with a commercial contractor who specializes in sampling utilizing low-flow techniques.

Table 32. Typical costs (per day) for the installation and development of direct push wells (non-demonstration).

	Well Installation			*Development*	*Sampling*
Activity	*Percussion* *$*	*CPT* *$*	*HSA* *$*	*$*	*$*
Planning & Contracting 15% of Labor Cost	$77	$77	$77	$39	$120
Labor[3] Prevailing Union Wage for Skilled Driller ($32.17/Hr.)	$514	$514	$514	$257	$800 [4]
Materials [5]	$13 [6]	$5.50	$4.50	--	--
Waste Disposal [7,8]	None generated	None generated	~1 drum per well	$150-$450 per drum	$150-$450 per drum
Well Protection	$75	$75	$75	--	--
Equipment [9] (Water Quality Meter, Surge Pumps, Tubing)	--	--	--	$125	$125
Rig & Support Truck [10]	$600	$1000	$500	--	--

Typical cost savings associated with direct push wells versus traditional wells are generally realized during the installation and well development phase. With few exceptions, operational costs are, in most cases, no different when compared to conventional monitoring wells. One possible exception would be in the case where exposed-screen type direct push wells were installed in a silty formation, which might silt-in more readily than conventional wells having traditional sand packs. In that case, additional cost would be incurred to redevelop the wells and dispose the purged water.

Another example where operational costs for direct push type wells might meet or exceed costs associated with conventional wells is in the case of small diameter (< 1-inch) direct push wells, specifically, when low-flow sampling protocol is specified. One of the

[3] Per Day Costs. Assumes a two-person crew for each well installation technology.
[4] Per Day Costs based on experienced two-person crew implementing Low Flow sampling techniques.
[5] Material costs are presented on a per foot cost.
[6] Materials used for the percussion wells are 1-inch inner diameter prepacked wells
[7] Based on a well 20 feet deep.
[8] Costs are approximate and vary with location and contaminant present.
[9] Per Day Costs. Includes calibration standards.
[10] Per Day Costs. Does not include mobilization or per diem.

criteria for low flow sampling is that a minimum drawdown of < 0.1 meters be maintained throughout the purging and sampling procedure. With small diameter wells, often a much lower flow rate is required in order not to exceed the maximum drawdown criteria. This typically increases the time required to complete the purging and sampling procedures thus increasing the cost of sampling.

6.2 Cost Comparisons to Conventional and Other Technologies

The scope of this project did not include the installation of any conventional wells, however, previous related work at NFESC did include the installation of conventional wells along with adjacent direct push wells. For the purpose of comparing costs between the two well installation technologies, cost data associated with the NFESC work is used (Kram, 2001). Although there are several research components involved, potentially leading to higher costs, well installation and development costs were tracked. These findings are summarized in Table 33. For the 24 DP wells (eight 2-inch wells and sixteen 3/4-inch wells), four days of installation were required to install approximately 385 feet of materials. Installation of pre-pack wells requires more time than the non-pack wells. Therefore, for non-pack devices, the same number of wells could be installed in approximately 2 days. Eight rotary drilled hollow stem auger wells (a total of 129 feet) were installed in 2 days.

The largest differences in the well installation costs were associated with the generation of solid and liquid waste. Solid soil cuttings were not generated for DP wells, except when required to set wellhead traffic protection boxes. However, this small amount of surface material is generally considered non-hazardous. For this project, liquid waste generation was 3 to 4 times higher for drilled wells. However, the liquid waste comparisons must be interpreted with caution, since high turbidity associated with augured wells was not simply due to the fact that more annular space disruption occurred. The sand pack material selection (based on ASTM standards applied to boring sample grain size distribution) may have also contributed to the level of turbidity (which was used to determine development end points).

Table 33. Demonstration costs and IDW comparisons for DP and Rotary Installed Wells.

	Direct Push Wells		*Rotary Installed Wells*
	Percussion	**CPT****	**HSA**
Well Diameter	2" and ¾"	2"	2"
Maximum Well Depth	20' (6.1m)	20' (6.1m)	20' (6.1m)
Average No. Installations/Day	6	8	4
Average Cost (Equipment and Labor)	$20/ft	$17/ft	$23/ft
Average Well Material Costs	$3/ft*	$5.50/ft	$6/ft
Solid Waste Generated	0 drums	0 drums	0.75 drums/well
Decon Rinseate Generated	~0.2 drum per ¾" well ~0.3 drums per 2" well	Same as Percussion	~1 drum/well
Average Development Water Volume	~10 gal/well per ¾" well ~15 gal/well per 2" well	Same as Percussion	45 gal/well

*Stainless steel prepack screens (2") cost $28/ft; Prepack schedule 40 PVC screens (3/4") cost $10/ft. All percussion and HSA cost data were provided by Mark Kram from NFESC.
** The CPT costs are typical (non-demonstration) costs provided by Applied Research Associates, Inc.

Several costs are not accounted for in Table 33. For instance, additional costs of approximately $4,200 for consumables (e.g., bentonite, sand, and grout), approximately $2,900 for mobilization, approximately $1,400 for subsistence, approximately $2,000 for surveying, approximately $2,400 for generation of boring logs, and approximately $2,400 for well development were also incurred. These costs were difficult to separate between drilled and pushed well activities, since these items are generally required regardless of the method of installation. In addition, several items (e.g., consumables, surveying activities, and generation of boring logs) are paid for on a sliding cost scale, whereby the greater the number of units, the lower the per unit cost. These general costs may be used to estimate anticipated costs when using different well designs. The least expensive alternative is to employ DP wells without annular sand pack. The most expensive approach would consist of using conventional drilling installation methods.

It is important to note that the cost difference between DP and drilled wells would most likely be much greater when used in a conventional production mode (as opposed to a research effort). For instance, the number of DP wells installed would be much higher for a conventional project (e.g., up to 15 DP wells per day in the same geologic setting), whereas the maximum number of HSA wells we've installed is 4 per day at the same site. The difference in daily production rate would lead to greater economies of scale on a large remedial investigation (RI) project than are evident from this small research study.

7. Regulatory Issues

7.1 Approach to Regulatory Compliance and Acceptance

Several actions were taken throughout the project to promote regulatory acceptance of the research program and its eventual results, and to assure compliance with applicable regulations at all field sites.

7.1.1. Regulatory Participation

During development of the project workplan, the research team held conference calls with regulatory review bodies including the Groundwater Monitoring Forum and the Direct Push Technology Forum. Both forums are composed of state and regional regulators. The draft workplan was reviewed by these bodies, and their comments were addressed in revisions leading to the final workplan. As well, the EPA Environmental Technology Verification (ETV) program actively participated in the development of the workplan and assisted in coordination of input from participating regulators.

The well comparison study was also presented to the Sampling, Site Characterization, and Monitoring 2002 Work Team of the Interstate Technology Regulatory Cooperation (ITRC) program at their annual kickoff meeting in Baltimore, MD on 7-8 February, 2001. The work team received the project enthusiastically, and it was found to meet all the criteria for ITRC involvement. These criteria include:

- There is a regulatory barrier;
- DOD and DOE are affected by the problem;
- The issue has broad national applicability;
- The effort builds on previous efforts;
- The product (e.g., findings) will set precedent;
- The outcome can be applied to other projects;
- Reciprocity among states can result from the project.

Funding for active involvement of the ITRC Sampling, Site Characterization, and Monitoring Work Team was not available until January, 2002. Consequently, their role to date has been as observers of the project.

7.1.2. DOD Task Force

In addition to the direct interaction of the project with regulator-only organizations, a DOD Task Force on Direct Push Ground Water Monitoring Wells was convened during one of the preliminary studies that fed into the current project. This task force also reviews the current study and has met during the planning and execution stages of the well comparison study. At the most recent meeting, they reviewed progress and findings to date and offered guidance on the design of a potential follow-on effort. The task force membership includes environmental regulators from the State of California, in which it has been estimated that 65% of the Air Force remediation budget is spent on monitoring.

7.1.3. Standards Preparation

In addition to design and execution of the well comparison study, another important task of the project was to assist in the development of an American Society for Testing and Materials (ASTM) standard. This standard, entitled "Standard Guide for Selection and Installation of Direct Push Groundwater Monitoring Wells" was authored and edited by members of the project team. In addition to providing practitioners with guidance on the use of DP wells, it is intended to provide regulators with a publication they can refer to as a benchmark for proper selection and installation of DP wells for investigating and monitoring remedial action sites. The ASTM Subcommittee on Direct Push Technology (D18-21) introduced the draft standard. The draft was revised and edited extensively by members of the project team to resolve all conflicts of opinion within the ASTM subcommittee during two balloting cycles at the subcommittee level. The draft standard passed a main committee balloting in September 2001, and will be published as *D 6724 Guide for Selection and Installation of Direct Push Ground Water Monitoring Wells* on the ASTM web site in the spring of 2002, and in the ASTM yearbook beginning in 2003.

7.1.4. Protocol Selection

To further assure regulatory acceptance of the research findings, protocols for sampling and analysis were chosen that are indigenous to the CERCLA and RCRA regulatory programs and guidance. These protocols, including SW-846 analytical methods and low-stress groundwater sampling, are discussed more thoroughly in the addenda to the work plan, and in section 5.2 Data Assessment.

7.1.5. Compliance

Regulatory agency Remedial Project Managers (RPMs) as well as owner site managers were consulted in the project planning stages to ensure that all required permits were obtained and all field activities performed under the project would be conducted in conformance with all applicable regulations. This generally meant that investigative derived wastes would be appropriately handled, and that worker activities would conform to site-specific health and safety plans (HASPs). Site-specific field operations plans and HASPs for the well comparison study were prepared and approved prior to the start of field activities and were adhered to throughout execution of the project.

8. Technology Implementation

8.1 DoD Need

As discussed in the Introduction section of this report, groundwater monitoring wells are a major element of nearly all contaminated site characterization, remediation, compliance, and post-closure monitoring efforts. Therefore, new technologies that reduce the cost of installing wells over conventional methods are needed and can have a pronounced impact on overall cleanup costs throughout the DoD complex. The magnitude of the potential savings is large considering that the DoD is steward of nearly 25 million acres of land in the United States alone (Defense Environmental Restoration

Program, 1996). Since the early 1980's DoD has acknowledged that there are nearly 30,000 contaminated sites, about half of which have not yet been cleaned up (U.S. EPA Publication EPA 540-R-00-007, 2000). Even if monitoring wells are installed at only 10,000 of the DoD sites awaiting cleanup, savings of just a hundred dollars per well can quickly add up to millions of dollars saved overall. In fact, savings in the tens of millions of dollars are more likely, considering that recent estimates place environmental cleanup costs at DoD sites in the vicinity of $30 billion (Tremblay).

8.2 Transition

8.2.1. Overall Project Performance

The current demonstration project has satisfied the major objectives set forth at the outset, many of which were designed to promote user acceptance of DP wells for long-term monitoring. Among the objectives that have been met are:

- Careful design of a technically rigorous research methodology for comparing the performance of DP wells to HSA wells;
- Generation of a consistent data set for conducting such a comparison, using regulatorily accepted field and laboratory protocols;
- Performance of appropriate statistical tests for evaluating the performance of DP wells versus HSA wells using a broad suite of analytes and other water quality measurements;
- Creation of a comprehensive project database to aid in management and analysis of the data set generated;
- Promulgation of an ASTM standard pertaining to the use of DP well for ground water monitoring;
- Active participation of industry as well as environmental regulatory committees and cooperatives;

One of the ways in which the technology will be transferred to the user is through the marketing and sales efforts of the DP industry.

Industry was involved extensively during the demonstration. Applied Research Associates, Inc. (ARA), a leading provider of CPT equipment and services including DP well installation participated directly on the project team and was responsible for executing many of design-related and analytical tasks within the project. Geoprobe Systems, Inc. (Geoprobe), the foremost manufacturer of percussion hammer DP platforms and related equipment conducted well installations at two of the test sites. In addition, ARA, Geoprobe, and many other industry players both contributed material to and participated in review of the ASTM standard that was created, and has been kept abreast of the progress of the project throughout its duration. The ASTM subcommittee on direct push technology (D18-21) includes representatives of 18 DP practitioners and 3 producers of DP equipment, and the subcommittee chair serves on the DOD Task Force on Direct Push Ground Water Monitoring Wells, which was actively engaged in the study.

8.2.2. Deficiencies

Although several project objectives were met unequivocally, one deficiency may be interpreted to exist in the *power* of the statistical tests that was ultimately achieved. The *power* of a test is defined as 1- β, where β is the probability of accepting a null hypothesis even though it is false. In the case of this study, the null hypothesis is that there is no difference between the results produced by DP versus HSA wells (e.g., the mean difference is zero). In other words, statistical *power* in this study is a measure of the ability to detect a significant difference between the two well types.

One reason why the tests lacked sufficient power may be that the study objectives changed subsequent to establishing the experimental design. Originally, the study was conceived as a gross comparison of DP versus HSA wells, admitting only the installation technique as a variable of interest. This plan called for aggregating the monitoring results from similarly constructed DP wells for the purposes of hypothesis. For instance, 2" and 1.5" diameter with no pack would be combined and all 0.75" wells regardless of pack type would be combined. However the objective was changed mid-project to one of evaluating each combination of DP pack type and diameter individually. Given the new objective, it is recommended that considerable more sampling rounds be undertaken to improve the power it the hypothesis tests.

8.2.3. Recommended Next Steps

The next step recommended for this study is to continue adding independent observation samples of DP versus HSA analytical results used in the statistical testing. This recommendation is directed towards improving the *power* of the statistical test of hypothesis. *Power* increases with the number of independent observations in a statistical sample (e.g., the number of sampling rounds conducted on the well pairs used for the study). With that in mind, recommendations toward increasing statistical *power* entail increasing the number of observations.

The first and least expensive manner in which the power of the tests can be improved is to add to the study database the data collected from Hanscom AFB in the AFRL-conducted well comparison study that preceded the current study in the years 1995-1996. The prior study was conducted on well pairs that were also used in the current study, and it adhered to identical sampling and analytical protocols. The DQOs of the current study would therefore be met by the pre-existing data, which could be incorporated into the project database and analyzed at marginal additional cost.

The second manner in which the power of the statistical tests can be improved is by continuing to conduct sampling on the existing wells used in the study. This is an advisable approach because additional observations can be generated without incurring the expense of additional well installations and attendant site coordination.

9. Lessons Learned

Although the objectives of the project were met successfully, there were a few lessons learned that could benefit future demonstrations.

Specifically, since an important objective of the project design was to maximize the statistical power as well as confidence of the experiment, future experiments would benefit from minimizing the number of variables (e.g., well diameter, sand pack verses no sand pack, screen depths, etc.) associated with the study. This will result in increased power of the statistical results, since all analytical data could be combined to increase the degrees of freedom. (See Section 5.3.1 for a discussion of these variables and their interrelations.)

Also, future experiments aimed at providing a statistical comparison would benefit from a two-phased implementation. The first phase should conduct a limited sampling of the population to be tested, with the aim of establishing characteristics of the population (e.g., mean, standard error, normality, etc.). Once these characteristics are defined, the experiment can be specifically designed to achieve the desired power and confidence in the second phase.

Finally, since there appears to be no guidance published for comparing intra-laboratory QA splits from two different methods, future experiments would benefit from using identical analytical methods for both QA samples and primary samples.

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